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CRITICAL REVIEW

Recent development of the novel riveting processes

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Abstract
Riveting process is widely used to join sheets by using rivets. It can be used in many fields due to its simple process, easy disassembly, and high reliability. In addition, it has incomparable advantage in the joining of light alloy, composite, and dissimilar materials. Conventional riveting belongs to mechanical joining. However, with the advancing of technology, it has been modified and combined to other joining techniques so as to improve mechanical properties of joint. The state-of-art riveting technologies in recent years are reviewed. Modified methods which originate from existing riveting techniques, such as reshaped riveting, restored riveting, self-piercing riveting, clinch riveting, electromagnetic riveting, flow drill screwing, and rivtac, are introduced. Many types of welding have been combined to riveting. Hybrid methods such as laser-arc welding assisted riveting, resistance rivet welding, friction riveting, friction stir blind riveting, friction self-piercing riveting, and friction element welding are also introduced. Latest researches on different riveting techniques have been listed. Forming mechanism of each riveting technique has been discussed. Process parameters that affect mechanical properties of joint have been analyzed. Merits and demerits of each technique have been introduced. Each craft has its own features and can be applied in certain circumstances. Some suggestions on future orientation of riveting are given in text to assist further investigation.

Keywords Riveting · Welding · Light alloy · Hybrid joining

1 Introduction

With the development of automotive industry, new materials which have high mechanical properties as well as low density are used more and more widely. The application of multi-material is becoming a trend in manufacture industry. However, physical and thermal properties of new materials are quite different from that of conventional material. This brings challenge to joining of new materials and much investigation has been done by researchers to achieve high quality joining.

Bolting is a joining technology that has a history of more than 500 years [1]. Bolt is inserted in the predrilled hole, and on the other side, a nut is assembled to the bolt to fasten two parts. Atas et al. [2] utilized bolting to join carbon fiber reinforced plastic (CFRP) sheets. They found that the continuity of CFRP sheets is destroyed due to the existence of predrilled hole, leading to high stress concentration in the periphery of hole. Therefore in bolting structure, joint is the place which has the lowest strength. Chishti et al. [3] investigated the influence of clamping torque on joint quality. It was found mechanical properties of joint can be enhanced by increasing clamping torque. However, due to low ductility of composite material, cracks may appear on CFRP sheet when too large clamping torque is implemented. Thus, it is essential to select a proper clamping torque. Kelly et al. [4] researched the effect of bolt-hole clearance on joint quality. Results showed that contact area between bolt and hole decreased with the increase of bolt-hole clearance. This led to severe stress concentration and reduced strength of joint. So large bolt-hole clearance should be avoided in bolting structure. Bolting has the advantages of easy assembly and disassembly, and brings convenience to checking, replacement and repairing. Yet, its application is limited in certain fields such as aviation. Vibration generated during flying process will cause loosing of bolt and brings disaster to flight. Thus, more stable joining is needed.

Resistance spot welding (RSW) is the mainstream steel joining technology in automotive industry [1]. RSW refers

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to the welding method that utilizes resistance heat generated by current passing through workpiece to heat the workpiece locally. It has the advantages of high stability, small deformation on workpiece and easy to achieve automation. However, KAŠČÁK et al. [5] pointed out that common resistance spot welding was not suitable for joining light alloy such as aluminum alloy. Since surface oxide layer, high thermal conductivity and low melting points would pose problems to the forming of a qualified joint. Despite this, researchers have tried every means to achieve welding between dissimilar materials. Chen et al. [6] found that the thickness of intermetallic compounds (IMCs) layer had a great effect on strength of welding joint. In order to produce joint with sufficient strength, proper IMCs thickness must be ensured. Lu et al. [7] applied ultrasonic in RSW. An aluminum insert was first welded to steel sheet with the help of ultrasonic. Then, aluminum insert acted as medium and was welded to aluminum sheet by conventional RSW. Zhang et al. [8] invented metallic bump assisted RSW. RSW was made possible by printing bump on the surface of sheet since bump possessed better wettability. Yi et al. [9–11] reviewed brazing between glass and metal and proposed some methods to solve the problem of residual thermal stress in brazing process. Li et al. [12, 13] reviewed some special means of brazing and found that the application of ultrasonic can improve the joining properties between dissimilar materials. Though these methods can achieve effective joining, the craft is too complicated and the cost is high.

Mechanical clinching, which can join parts with no auxiliary element [14–16], arouses increasing interest among researchers in recent years. Mechanical clinching is a cold forming process. Sheets are pressed by punch and deformed, forming a mechanical interlock that hooks lower sheet [17–19]. Sheet with coating or painting on surface can be joined directly without damaging surface. Failure mode of clinched joint was researched by Lei et al. [20]. Three failure modes, which are neck fracture, bottom separation, and mixed fracture, were found in strength tests. In order to increase mechanical properties of clinched joint, finite element analysis was conducted by Dean et al. [21] to optimize geometrical parameters of forming tools. Extensible dies have also been used by Lambiase et al. [22] to assist material flow of sheets when forming. Chen et al. [23] investigated reshaped clinching which can reduce protrusion height as well as enhance joint strength. Besides, Chen et al. [5, 24, 25] researched flat clinching so as to apply clinching in visible area where a beautiful surface is required. Peng et al. [26] reviewed various novel technology developed on the basis of clinching and introduced their application in industry. Despite the advantages of clinching such as easy craft, low cost and high efficiency, the strength of clinched joint is relatively low [27–30]. It is not competent in the circumstance where a high strength joint is demanded.

Unlike mechanical clinching, riveting is a joining technique that joins parts with auxiliary element. Martinsen et al. [1] divided joining technology into 3 categories, which are mechanical joining, chemical joining and thermal joining. Early riveting is classified as mechanical joining. However, it no longer restricts to its original field. In order to satisfy the need of production and life, various kinds of rivets as well as riveting techniques have been invented. This paper reviewed novel riveting technology in recent years. Latest researches on different riveting techniques have been introduced. Merits and demerits of each technique have been discussed and analyzed. Future orientations of riveting are also presented.

2 Normal riveting technology

Conventional riveting is a mechanical joining technology that utilizes plastic deformation of rivet to join sheets. Schematic of conventional riveting is shown in Fig. 1. Holes need to be drilled in advance on both sheets. Rivet is put in the hole of sheets, with factory head being fixed by lower die. Upper die is driven by hydraulic power or hammer hitting to punch the rivet. Rivet head is deformed under the impact, forming a protrusion that joins two sheets. Rivet shank expands and upsetting occurs. Interference fit is thus formed to further fasten the sheets. According to whether the process needs to be heated or not, conventional riveting can be divided into cold riveting and hot riveting. If rivet diameter is small, it is unnecessary to heat. If rivet diameter is large and rivet material is steel, hot riveting is needed to assist material flow. For rivet with shape being long and thin, head part of rivet needs to be heated so as to avoid fracture. Riveting joint can be fixed or flexible. For flexible joint, joining part can mutually rotate, such as joint on tongs, scissors and compasses. Shape of rivet head can be varied according to application circumstance. Rivet diameter, rivet length, and hole diameter need to be determined and matched by calculation since rivet shank bears shear load when working. Joint produced by conventional riveting can not only meet the demand of strength but also reach the requirement of watertight as well. However, some problems also exist in the application of conventional riveting. Interference fit produced by conventional riveting is not uniform and will bring hidden danger to stability of structure. When joining composite material, composite material will be damaged by impact if conventional riveting is carried out. Besides, the craft of predrilled hole will lead to low efficiency. All these defects restrict the application of conventional riveting.

Another normal riveting technology is blind riveting. Unlike other rivets being one part, blind rivet consists of two parts, which are rivet body and rivet stem. Rivet before the invention of blind rivet needs to be operated by tools such as hammer or die from both sides of sheets. After blind rivet was

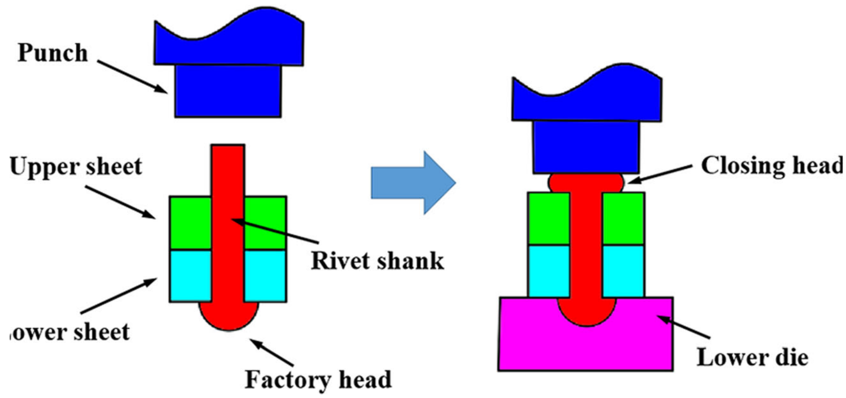


Fig. 1 Schematic of conventional riveting

invented, sheets can be bonded from one side, without any operation on the other side [31]. It is especially suitable on the occasion when conventional riveting cannot be conveniently conducted, such as hollow or tubular structure. A special tool, rivet gun, which can be manual, electro or pneumatic is needed when riveting. A notch, which will break when load reaches preset value, is predesigned at the rivet stem. The process of blind riveting is shown in Fig. 2. Rivet body is put in the hole of sheets. The clamp is used to fix the rivet stem. Then, rivet stem is pulled by operating rivet gun, causing rivet body to be squeezed and deformed. A mechanical interlock is thus formed. Rivet gun continues to pull until rivet stem breaks at the notch. Lower part of rivet stem remains in rivet body.

Though nowadays normal riveting is still used in many aspects, novel riveting whose joint has much better mechanical properties than that of normal riveting has been invented one after another. Thus, there are relatively few articles about these riveting in recent years and they are not the key points that will be discussed in this article.

3 Novel riveting techniques

Researchers have done much work to investigate novel riveting techniques that can achieve effective joining of advanced material. Various ways such as adding extra step or element, altering material, changing process parameters, replacing hydraulic power with electromagnetic force, using rivet with thread and combining riveting with welding are used. All the novel riveting techniques can be sorted into hybrid method which combines riveting with welding and modified method which originates from existing techniques. Comparison of different characteristics of riveting techniques is shown in Tables 1 and 2. Latest researches on novel riveting techniques are listed as followed.

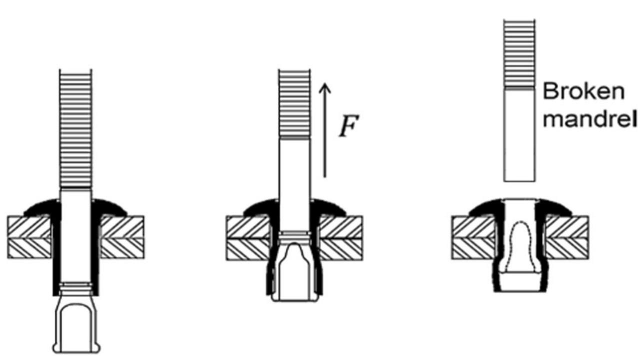


Fig. 2 Schematic of blind riveting [32]

3.1 Reshaped riveting

Clinching has aroused increasing attention in the joining of light weight material due to its high efficiency, low cost and ability to join coated sheets without damage. However, the protrusion of clinched joint restricts the application of clinching in visible areas where beautiful surface is required. A reshaped clinching which aims at reducing the protrusion height of clinched joint was investigated by Chen et al. [23]. They found that when thick sheet was placed as upper sheet, the strength of joint was higher [33]. Besides, reshaped clinching with additional rivet was further investigated by Chen et al. [34] so as to increase the strength of joint. This type of riveting consists of two steps, as is shown in Fig. 3. The first step is the same as mechanical clinching with extensible dies. The second step is to put a rivet in the hole of the joint, and then the sheets together with rivet are turned with the upside down. The joint is laid on a flat die and the protrusion of the joint was pressed by another flat die.

Forming force in reshaping step is an important parameter that affects quality of joint. Chen et al. [36] investigated the effect of forming force upon joint strength. It was found that with the increase of forming force, the strength of joint first increased, then decreased. Increasing forming force can increase interlock thickness of joint and reduce protrusion height. However, neck thickness of joint first increased then decreased with the increase of forming force. Chen et al. [34] also investigated effect of sheet disposal mode upon joint strength. Joint with upper sheet being AL6061 and lower

Table 1 Comparison of modified riveting techniques

	Reshaped riveting	Restored riveting	Self-piercing riveting	Clinch riveting	Electromagnetic riveting	Self-drilling Screw	Rivtac
Tensile strength	Low	Low	High	Low	High	Low	Low
Shearing strength	High	Low	High	High	High	High	High
Cost	Low	Low	High	Low	High	High	High
Energy input	Low	Low	High	Low	High	High	High
Complexity	High	High	Low	Low	Low	Low	Low
Pre-operation	Clinching	Damage	None	None	Predrilling hole	None	None
Time	Long	Long	Short	Short	Very short	Short	Very short
Punch force	High	High	Very high	High	Very high	High	Very high
Requirement for coaxial degree	High	High	Very high	Very high	High	High	High

sheet being AL5052 exhibited higher tensile strength, shearing strength and energy absorption than joint with upper sheet being AL5052 and lower sheet being AL6061. In both tensile test and shearing test, failure mode of reshaped joint was neck fracture due to bearing capacity of interlock was higher than that of neck, as is shown in Fig. 4. Fracture was caused by tensile or shearing strength of joint surpasses yield stress of material. When fractured, rivet was still kept in upper sheet and part of upper sheet remained in lower sheet. Thin neck will cause joint to be fractured easily and thus increasing neck thickness is the main method to improve joint strength.

Mechanical properties of reshaped riveting joint were researched by Chen et al. [35] and was compared to clinched joint, reshaped joint with flat die and reshaped joint with bumped die. The schematics of forming processes are shown in Fig. 5. The protrusion height of all the joints was reduced to same in reforming process. The forming force of reshaped riveting is the highest due to plastic deformation of rivet. In strength test, it was found that tensile load, shearing load and absorption energy of reshaped riveting joint were the largest, while that of clinched joint was the lowest. All joints were failed in the same failure mode which is neck fracture. Cross-section was obtained to measure geometrical parameters. Clinched joint has the least neck thickness and then in increasing order are reshaped joint with flat die, reshaped joint with bumped die and reshaped riveting joint. This was consistent with the strength order of corresponding joints, indicating that neck thickness can represent the strength of joint. It can be concluded that all forming methods increase the strength of joint by increasing neck thickness. The final shape of reshaped riveting joint is similar to that of clinch riveting joint, which is invented by Mucha et al. [37] and has tensile strength two to three times than normal clinched rivet. Chen et al. [38] also carried out finite element analysis to simulate the process. Optimal geometrical parameters of rivet were obtained by orthogonal test as well as range analysis.

Though reshaped clinching can effectively improve the strength of clinched joint, it also increases the complexity of the joining process and reduces the efficiency correspondingly. How to simplify the process requires further research. Besides, rivet will inevitably increase the weight of joint. Using tubular rivet instead of solid rivet is a way to solve this problem. Future work should be carried out to explore whether it can reach the same strength as solid rivet.

Table 2 Comparison of hybrid riveting techniques

	Laser-arc welding a ssisted riveting	Resistance rivet welding	Friction riveting	Friction stir blind riveting	Friction self-piercing riveting	Friction element welding
Strength	Very high	High	High	High	Very high	Very high
Surface	Cleaning	Cleaning	None	None	None	Cleaning
Energy input	Very high	High	High	High	Very high	Very high
Complexity	High	High	Low	Low	Low	Low
Time	Long	Long	Short	Short	Short	Long
Environment friendliness	Suboptimal	Good	Good	Good	Good	Good

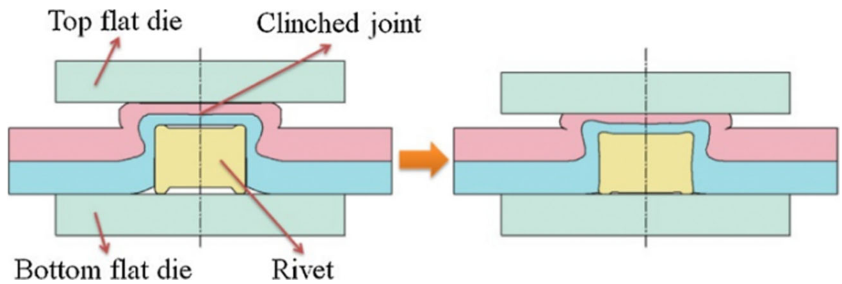


Fig. 3 Forming process of reshaped joint [35]

3.2 Restored riveting

Generally, a clinched joint will have to be scrapped when it is damaged. This will inevitably cause wasting of material and bring problems to people when circumstances make it difficult to form a new clinched joint. Therefore, Chen et al. [39–42] invented a new restored riveting process that can renovate the damaged clinched joint. The material of the sheets used in experiments was Al5052 due to its high plasticity, and rivet material was Al6061. The process is shown in Fig. 6. Two sheets were joined by mechanical clinching, then the sheets were pulled to failure under shearing load and the joint was fractured at the neck. After the joint was damaged, the broken parts were picked up and were assembled to its original shape. A rivet was put in the hole of the clinched joint and the sheets were placed on the surface of a flat bottom die. Then, the sheets were pressed by a flat die with a speed of 0.05 mm/min. The maximum load was set to 35 kN, imposed by Instron 5982 machine. During the renovating process, the diameter of the rivet bottom part was increased due to material flow. A new interlock was formed in the shape of "C" to hook rivet and upper sheet.

Chen et al. [39] investigated the properties of the renovating joint. Shearing test was carried out on the renovating joint. Results showed that shearing strength and energy absorption of renovating joint was higher than that of clinched joint, but lower than that of reshaped riveting joint. Unlike clinched joint with failure mode being neck fracture, the failure mode of renovating joint was separation mode, as is shown in Fig. 7. The cross-section was observed and showed that neck thickness of clinched joint, reshaped joint and renovating joint were almost the same. Usually, geometrical parameters of joint can represent joint properties. But in this experiment, joints had similar neck thickness yet presented rather different mechanical properties. Two reasons led to this kind of phenomenon. The first was that rivet placed in the joint bore part of shearing force and relieved the load which was originally applied on the neck. The second was that the failure mode of reshaped riveting, which is neck fracture, is different from that of restored riveting joint. Chen et al. [40] also researched effect of renovating force upon joint shearing strength, and optimal renovating force was obtained by experiment.

The reliability of restored riveting joint in tensile and shearing test has been proved. However, in practical use, the condition which joint faces is much more complicated. Since sheets have been damaged before forming of joint, the corrosion behavior and fatigue strength of joint needs to be further investigated. Moreover, all the joints that have been restored fail in neck fracture. Joints fail in other failure mode, such as bottom separation and mixed fracture can also be restored and researched.

3.3 Self-piercing riveting

Self-piercing riveting is a cold forming joining technology [43] that presses the rivet directly into the sheets powered by hydraulic cylinder or servo motor. This technology overcomes many disadvantages of conventional riveting, such as poor

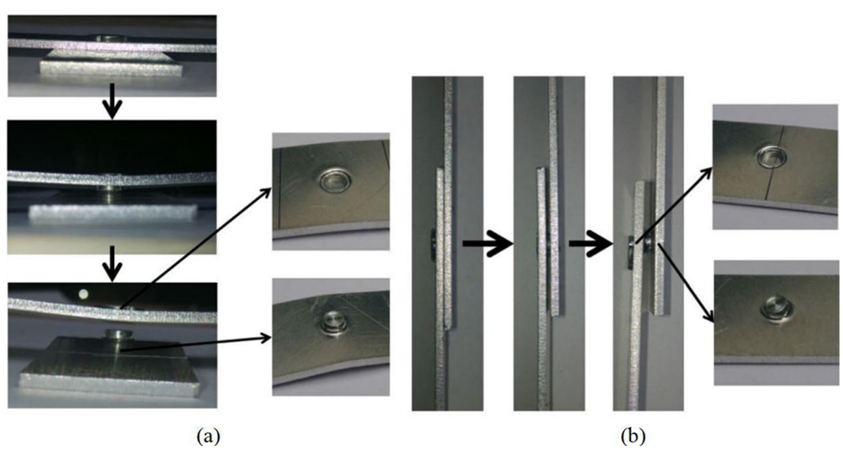


Fig. 4 Neck fracture of joint in (a) tensile test and (b) shearing test [36]

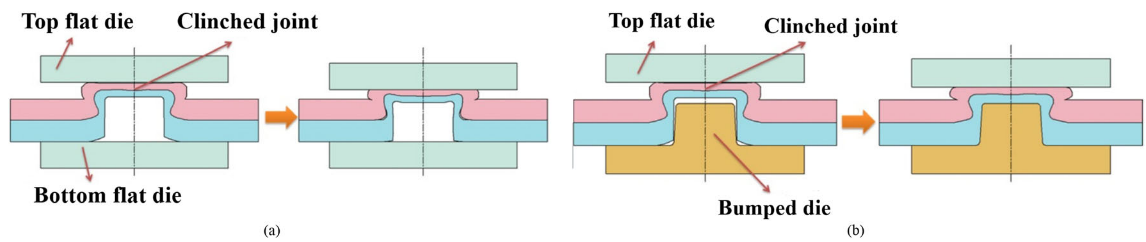


Fig. 5 Forming process of (a) reshaped clinching with a flat die and (b) reshaped clinching with a bumped die [35]

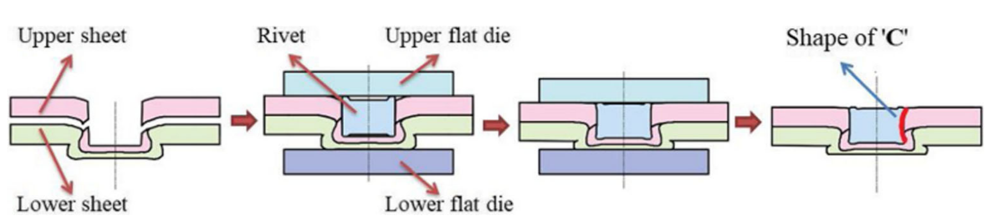
appearance, low efficiency and complicated craft [44–47]. Punching and riveting can be achieved at one time and coated sheet can be joined without destroying the coating. Semi-tubular rivet is the most commonly used rivet in self-piercing riveting. Not only does the joint it produced possesses high static and fatigue strength, but can reduce the weight of structure greatly.

The process of self-pierce riveting is shown in Fig. 8 [48]. The blank holder moves downward to firmly compress the sheet and rivet is pushed by punch to get in contact with upper sheet. Punch pushes the rivet and forces it to pierce upper sheet. In the same time, the rivet drives lower sheet to deform plastically towards female die. During the process of riveting, rivet tail gradually expands, lower sheet material together with rivet deforms plastically and fills the female die. Under the joint effort of punch and female die, rivet tail inlays in lower sheet and form a mechanical interlock that firmly hooks two sheets. The riveting process is thought to be completed when upper surface of rivet head is the same height as upper surface of upper sheet. Then, blank holder releases blank holder force and punch returns to its original position.

Cross-section of SPR joint is shown in Fig. 9. Undercut thickness (Δu), bottom thickness (Δb), head height (H), and remaining thickness (Δr) are main geometrical parameters that affect joint quality. Undercut thickness refers to the horizontal distance between lower edge of upper sheet and outer edge of rivet tail. The larger the undercut thickness, the deeper rivet tail inlaying in lower sheet. Thus, the degree of mechanical interlock between rivet and lower sheet is higher, along with higher strength of the joint. Head height refers to the coaxial distance between rivet head and upper sheet. In order to obtain a beautiful surface and achieve high degree of flatness, the value of Z is usually kept below 0.3 mm. If the value of Z is less than 0, upper sheet will be damaged and stress concentration will occur around rivet head. Bottom thickness refers to axial thickness between the tip of rivet tail and lower surface of lower sheet. Remaining thickness refers to the thickness of thinnest part of lower sheet inside the rivet tail. Both the bottom thickness and remaining thickness are used to evaluate the strength and sealing effect of lower sheet after riveting. Too mall of these two value indicated that the strength of lower sheet is too small and fracture may appear on the joint.

Researchers have done much work to investigate the influence of various process parameters on joint quality. Li et al. [51] investigated geometry of rivet tip. Results showed that rivets which had a sharper tip flared more in the forming process, enlarging undercut thickness and bottom thickness. Rivet used in SPR is usually made of high strength steel. Hoang et al. [52] utilized SPR to join 6060 sheets, with rivet material being 7278. This can be achieved with the help of heat treatment and strength of rivet need to be higher than that of sheets. Experiments showed that if rivet material was too soft, rivet would appear massive plastic deformation, let alone piercing upper sheet. If rivet material was too hard, small expansion of rivet would be insufficient to form an enough undercut thickness. Thus, it is vital to select a proper rivet material by experiment or finite element analysis, as is discussed by Li [48] in his review. Li et al. [53] researched the effect of die profile on joint quality. It was found that when high strength material was placed as lower sheet, dies which had a deep cavity or sharp corners had higher tendency to produce serious fracture on lower sheet. Khanna et al. [54] investigated strength of joint with different sheet thickness. When thickness of upper sheet was equal to that of lower sheet, rising of sheet thickness would enhance joint strength. When thickness of upper sheet was different from that of lower sheet, joint strength mainly depends on sheet which had a smaller thickness. It can be concluded that as thickness ratio of upper sheet and lower sheet rose, joint strength would become lower.

Fig. 6 Restoring process of damaged joint [42]



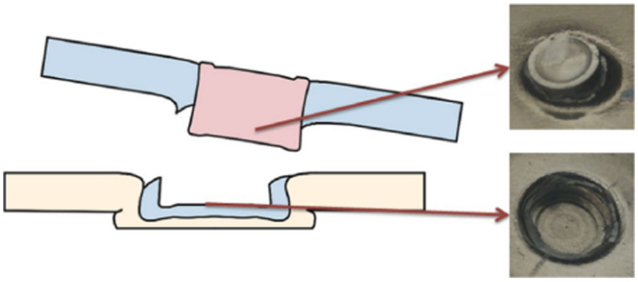


Fig. 7 Failure mode of restored riveting joint [39]

Recent development of self-piercing riveting mainly focuses on joining of new material, such as composite material and light alloy. Zhang et al. [55] researched the influence of disposal mode on joint quality. Both CFRP and glass fiber reinforced plastic (GFRP) were joined to aluminum alloy in different disposal mode. It was found that CFRP sheet had to be placed as lower sheet when joining. CFRP possessed high strength as well as low ductility and would easily craze if it was placed as upper sheet, since deformation of upper sheet was much larger than that of lower sheet in SPR. In joint with sheets being GFRP and aluminum, two failure modes could be found. One was pulling out of rivet; the other was bearing damage of sheet. When aluminum was placed as upper sheet, rivet was firmly wrapped by aluminum and was pulled out from GFRP in shearing test since interlock is weak. When aluminum was placed as lower sheet, bearing damage appeared on GFRP sheet due to high strength interlock and brittleness of GFRP. Liu et al. [56] utilized SPR-bonding hybrid method to join CFRP sheet and aluminum sheet. They found that ply angle of CFRP sheet had an important effect on strength of joint. In all the specimens tested, joints with 0°/90°ply angle possessed highest static strength, while joint with ±45° ply angle possessed the lowest static strength. Gay et al. [57] investigated the fatigue performance of SPR joint. They utilized SPR to join aluminum and glass fiber reinforced thermoplastic composite and conducted lap-shear fatigue test on joint. Composite was placed as upper sheet. Results showed that material and temperature had more impact on fatigue properties of joint than process parameters. As temperature rose, fatigue strength of joint decreased greatly due to high temperature sensitivity of composite. They also found that when composite was too thin, joint failed in the manner of rivet pullout for both countersunk rivet and domed rivet, as is shown in Fig. 10(a), (b). For joint with enough composite thickness, failure modes are shown in Fig. 10(c)–(e). When load was low, transverse crack appeared around rivet and composite was separated into two parts. When load was in an average level, rivet was pulled out, along with holding and tearing of composite. When load was high, rivet pullout caused severe deformation of composite.

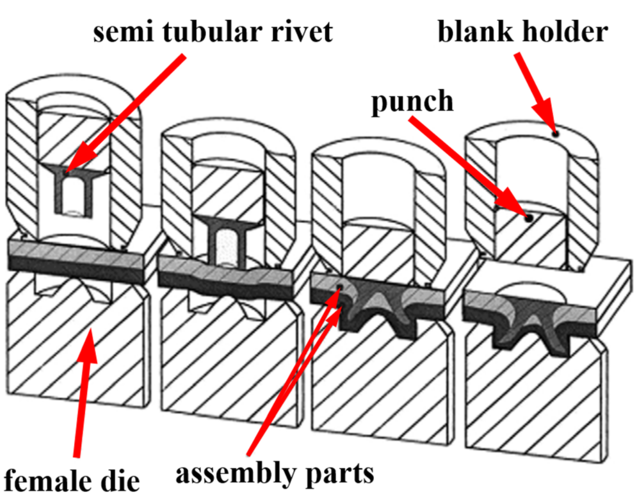


Fig. 8 Schematic of self-piercing riveting [49]

In order to evaluate the properties of joint, two methods have been adopted and widely used. One is destructive testing method, and the other is online monitoring method. Destructive testing method including observing cross-section and carrying out strength test such as tensile test, shearing test and fatigue test on joint to obtain strength. Though destructive testing method is direct and reliable, the efficiency is too low and cost is too high. Besides, it cannot reach the checking rate of 100%. Therefore, it is not suitable for quality inspection in automated mass production. Online monitoring method is a universal used method in factory, the principle of which is to judge the joint quality by monitoring the force displacement curve during riveting process. Johnson et al. [58] applied computer vision in online monitoring system, further increasing the accuracy of measurement.

After decades of development, SPR has become a mature technique to join light weight and dissimilar material. Yet, it still has room for improvement. Due to the usage of lower die, the protrusion of SPR joint is larger than other riveting, which limits its use in compact space. Research on usage of flat die in SPR is worthwhile. In addition, joining material which has high strength and low ductility is a challenge for SPR. The effect of assistant measure such as heat treatment needs to be further investigated.

3.4 Clinch riveting

The craft of clinch riveting is to compress the rivet into sheet without piercing it [37, 59–61]. Forming process of clinch riveting is shown in Fig. 11. Rivet is put on the surface of upper sheet. The punch which is driven by hydraulic power compresses the rivet into sheet until lower surface of punch is the same height as upper surface of upper sheet. Extensible die which has movable segment is used to assist material flow of sheets. Top and bottom part of rivet flares under the combination effect of outer force and extensible dies, forming a mechanical interlock that joins two sheets.

Clinch riveting has many advantages such as no need to drill a hole in advance and possessing high joining speed. Steel

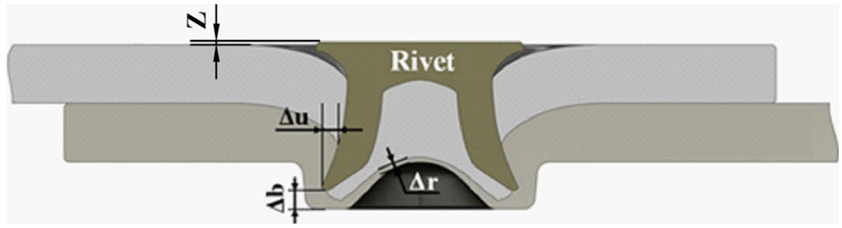


Fig. 9 Cross-section of joint produced by self-piercing riveting [50]

sheets are usually galvanized to prevent corrosion and improve appearance. Coating on the sheet surface, which will bring a lot of problems to welding, needs to be cleaned before resistance spot welding. However it is unnecessary for clinch riveting to do so since no thermal and chemical reaction is involved. The equipment of clinch riveting is even similar with that of spot welding, which makes it convenient to be adopted by factories. Compared with self-piercing riveting, it has better anti-corrosion property because only plastic deformation occurs during joining process, with no damage on sheets.

Spišák et al. [61] compared mechanical properties of clinch riveting joint with that of clinched joint by conducting shearing test. It was found that strength of clinched joint was much lower than that of clinch riveting joint. Failure modes of two joints in shearing test were different. Clinched joint failed at the neck, with part of upper sheet material remaining in the hole of lower sheet. While in failure mode of clinch riveting joint, rivet was completely pulled out from lower sheet and remained in upper sheet, as is shown in Fig. 12. Cross-section of clinch riveting joint was observed by KAŠČÁK et al. [37] and crack was found in joint, as is shown in Fig. 13. The influence of crack upon strength of joint in clinch riveting was not as severe as in clinching, since rivet bore main part of load. Similar to clinching, mechanical properties of clinch riveting joint can be judged by neck thickness (t_n) and interlock thickness (t_u). Bottom thickness (t_b), which refers to thickness of the thinnest part where sheets have been compressed, is another important parameter that affects tightness of joint. Mucha et al. [63] investigated the effect of material stack on joint strength. It was found that joint with different sheet disposal modes presented different cross-section and mechanical properties.

Generally, rivet used in clinch riveting process is made of steel. Compared with steel, the strength of aluminum alloy is much lower. When the rivet is compressed into the sheets, severe plastic deformation will be generated on the rivet which is made of aluminum alloy. Thus, it is challenging to join sheets by using aluminum alloy rivet in clinch riveting process. However, KAŠČÁK et al. [64] successfully applied aluminum rivet in the joining of steel sheets. Two sheet samples were used in experiment. One was made of H220PD steel and the other was made of DX51D+Z. Resistance spot welding was also conducted on steel sheets so as to compare the carrying capacity of joint produced by clinch riveting and resistance spot welding. Shearing test was carried out to evaluate mechanical properties of joint. It was found that shearing load of welding joint was higher than shearing load of clinch riveting joint in all samples. Shearing load of clinch riveting joint on H220PD steel sheets was similar to that of DX51D+Z steel sheets. While shearing load of welding joint with different sheet material was rather different. Maximum shearing force of welding joint on DX51D+Z steel sheets was approximately 2000 N higher than that of H220PD steel sheets.

Shearing strength of joint has been greatly improved by existence of rivet, while tensile strength of joint is low compared with other riveting such as SPR. This is because the forming mechanism of interlock is similar to that of clinching. The effect of rivet is to guide material flow. In order to increase the thickness of interlock, rivet of different shape and material needs to be further investigated. Besides, it is difficult to ensure the coaxial degree between rivet and lower die. Installing method is a focus for future research.

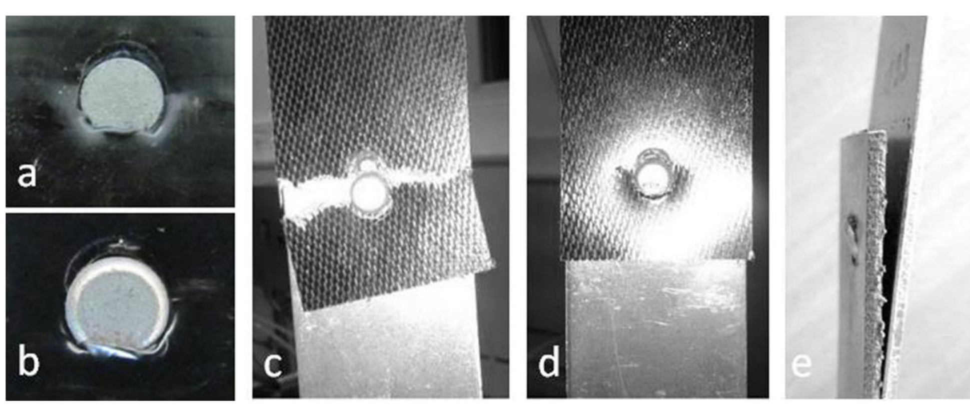


Fig. 10 Failure mode of SPR joint in lap-shear fatigue test. (a) Countersunk rivet with thin sheet. (b) Domed rivet with thin sheet. (c) Thick sheet under low load. (d) Thick sheet under average load. (e) Thick sheet under high load [57]

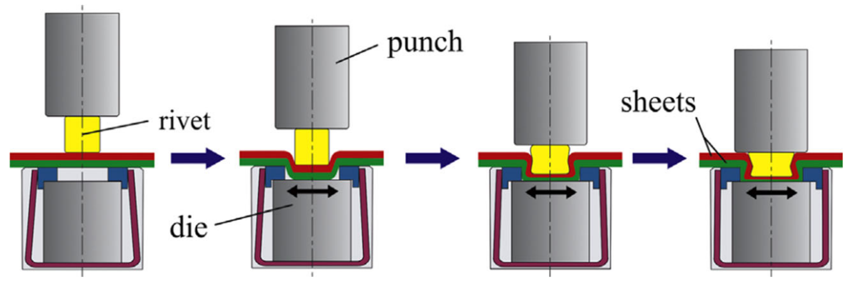


Fig. 11 Forming process of clinch riveting [62]

3.5 Electromagnetic riveting

Electromagnetic riveting (EMR), also known as stress wave riveting, is a new riveting technology that utilizes Lorentz force to deform rivet [65–68]. Principle of electromagnetic riveting [69] is shown in Fig. 14. Capacitor discharges towards coil after switches are closed, generating powerful pulse current in the coil along with formidable pulse magnetic field that surrounds the coil. The driver plate produces heavy eddy current due to electromagnetic induction. The direction of magnetic field which produced by eddy current in driver plate is opposite to the direction of pulse magnetic field produced by coil. Punch is driven by mutual repulsion between two magnetic fields to deform the rivet [70–72]. Due to high speed of impact load and transmitting mode of load being stress wave, electromagnetic riveting is also named as stress wave riveting.

The appearance of adiabatic shear band (ASB) is an important characteristic of electromagnetic riveting [73–75], as is shown in Fig. 15. Due to large impact and high speed, forming is accomplished within 1.4 ms. Thus, the forming process is very close to adiabatic process. Plastic deformation has a high degree of localization, with stress highly concentrating in narrow ASB. Cui et al. [76] researched forming mechanism of ASB. It was found that ASB was formed under the combination effect of uneven material flow and heat softening. Zhang et al. [77] also predicted the appearance of ASB by finite element analysis.

Interference fit can prolong fatigue life of joint [75, 78] and becomes a main method at present to extend structure life. When sheets are joined by normal riveting, rivet rod expands unevenly, especially for thick structure. So it is hard to ensure that all part along rivet rod has interference and is difficult to achieve optimal fatigue life. Song et al. [74] investigated interference fit of joint produced by electromagnetic riveting. Since forming time was very short, expanding of rivet rod and upsetting of rivet head almost happened at the same time. Thus, interference fit of EMR joint was much uniform than normal riveting. This feature makes it suitable for joining composite materials. Composite materials which have a low ductility will be squeezed and damaged in conventional riveting due to uneven expanding of rivet rod. Jiang et al. [79] utilized EMR to join CFRP sheet and aluminum sheet. Numerical model was also established to simulate the process. It was found residual stress along rivet hole was uniform and CFRP sheet was not damaged around rivet hole. Simulation result was in highly accordance with experiment.

Much work has been done to investigate the influence of various process parameters upon mechanical properties of electromagnetic riveted joint. Jiang et al. [69] researched joint with different locking modes. Three locking modes SR, RC and RA are shown in Fig. 16 and were tested in experiments. Results showed that riveted joint with locking mode being SR had the most uniform interference and a relatively stable shear performance. RC joints had the highest shearing strength and absorption energy. Discharge energy also had an obvious influence on joint quality. As discharge energy rose, diameter of driven head as well as rivet interference would become larger, ASBs would be more evident and damage of CFRP sheets would be more severe. They compared the effect of locking

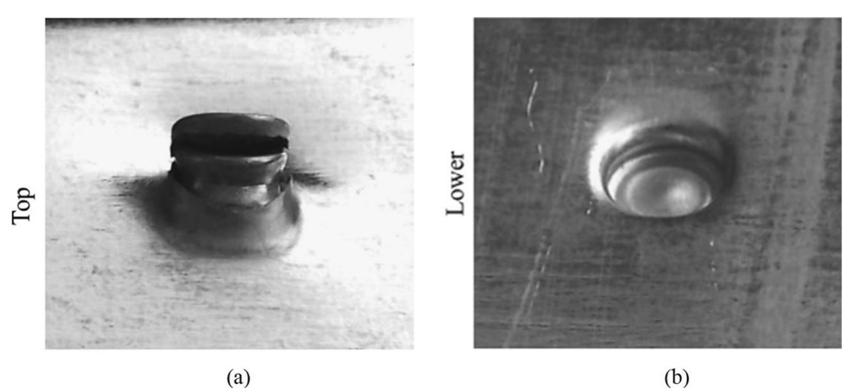


Fig. 12 Failure mode of clinch riveting joint. (a) Upper sheet. (b) Lower sheet [62]

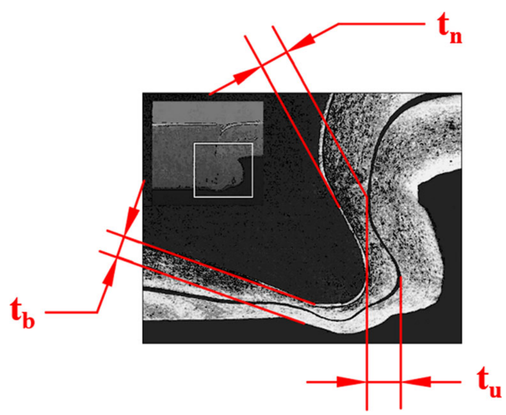


Fig. 13 Cross-section profile of joint produced by clinch riveting [63]

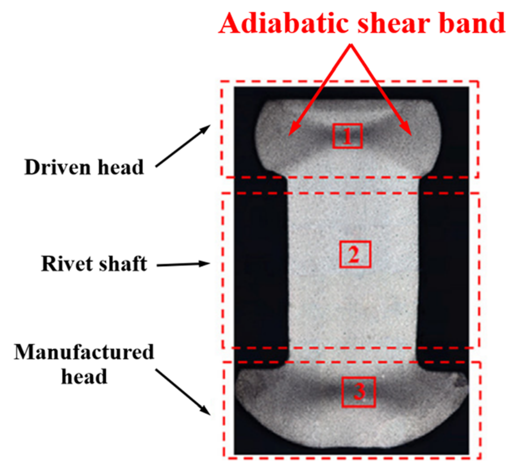


Fig. 15 Adiabatic shear band of EMR [65]

mode with that of discharge energy by weight analysis. Results showed that the influence of locking mode on joint quality was greater than that of discharge energy. Jiang et al. [80] also investigated the influence of rivet die on fatigue performance of joint, as is shown in Fig. 17. It was found that joints with special die performed better than joints with flat die in tensile fatigue test. This was because material flow of driven head in radial direction was restricted by special die. The expansion of rivet rod and interference fit of joints became larger due to more materials were squeezed into the hole. Thus, mechanical properties of joint were enhanced. Joint with 8° die angle performed best in tensile fatigue test, for it had a more homogeneous interference fit.

Most researches on electromagnetic riveting focus on laboratory application, ignoring its application in practical manufacture. High manufacture efficiency needs to be achieved by high degree of automation and application of industrial robot is an effective way to realize automation. However, due to large impact in electromagnetic riveting, vibration which will cause angle deflection of robotic arm will inevitably occur. Besides, assembly tolerance of device as well as micro-

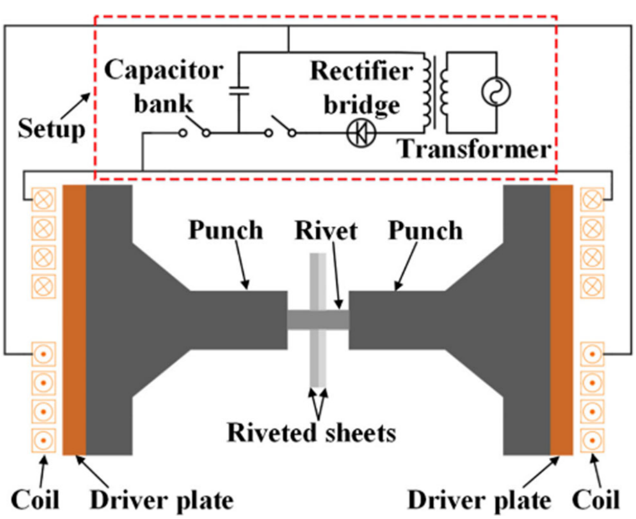


Fig. 14 Principle of electromagnetic riveting [69]

deformation of material will also contribute to angle deflection. Therefore, it is necessary to research effect of angle deflection on joint quality. Duan et al. [81] investigated it by experiment. Joints formed with different angle deflection were tested, as is shown in Fig. 18. Rivet shaft as well as driven head would tilt when upsetting. This would produce a clearance between shaft and sheets, affecting interference fit of joint. In driven head, adiabatic shear band in a shape of X was formed. Unlike joint without angle deflection, adiabatic shear band of joint is not symmetrical, with lower-left and upper-right part much obvious than that of upper-left and lower-right. Failure modes of joints formed with different angle deflection were different, as is shown in Fig. 19. When carrying out tensile test, joint formed without angle deflection failed at manufactured head, while joint formed with 6° angel deflection failed at driven head. Driven head was pulled out from holes in joints formed with 2° and 4° deflection angle. It can be concluded that rising of angel deflection will augment clearance length while reduce relative interference, thus reduce mechanical properties of joint. As long as requirement of strength is reached, rejection rate can be lowered by lowering design reliability of structure. In situation where reliability demand is not high, joint with angle deflection not exceeding 4° is acceptable.

Electromagnetic force has been applied to self-piercing riveting and so was born the electromagnetic self-piercing riveting. Liang et al. [82] compared mechanical properties of ESPR joint with that of conventional SPR joint. It was found that ESPR joint had a larger undercut thickness and higher rivet tail hardness, resulting in better mechanical properties. Jiang et al. [50] utilized ESPR to join steel/Al (S-A) and CFRP/Al (C-A). Aluminum sheet was placed as lower sheet in both joints. Results showed that undercut thickness as well as interlock of C-A joint was higher than that of S-A. Since in S-A joint rivet inserting was restricted by rivet tail upsetting. However, shearing strength of S-A joint was higher than that of C-A joint due to high plasticity of steel sheet and

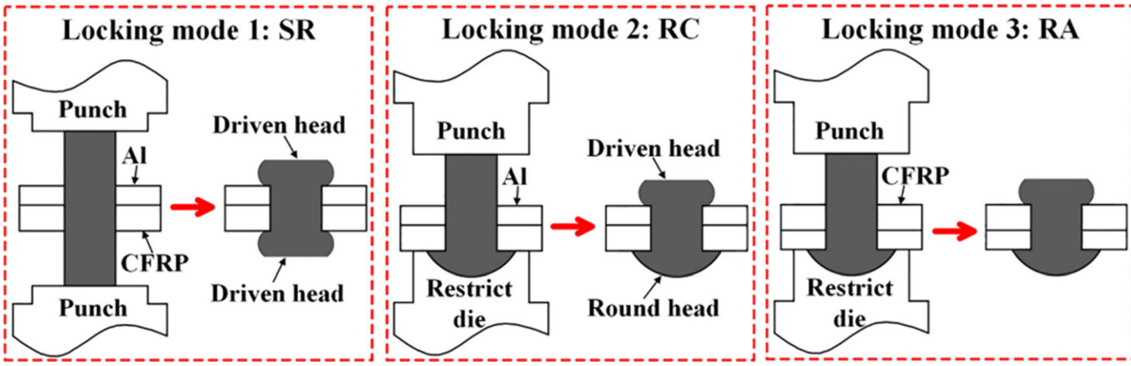


Fig. 16 Three locking modes of riveted joint [69]

reinforcement of joint by rivet upsetting. They also researched the effect of loading speed on mechanical properties of joint. It was found that shearing strength of joint increased with the increase of loading speed, while absorption energy of joint decreased with the increase of loading speed. This was because as loading speed rose, resistance between rivet and sheet would rise, while friction between two sheets would fall. Besides, under high loading speed, deformation of sheets in shearing test was smaller, resulting in smaller absorption of energy. Jiang et al. [83] investigated influence of rivet structure on mechanical properties of joint. It was found that for different sheet combination, geometrical parameters of rivet which can achieve optimal joint strength were different.

Due to the high speed load of EMR, micro cracks appear in rivet head, and cracks become more severe with the increase of rivet hardness. In order to prevent the appearance of cracks, further research on EMR needs to be conducted. Moreover, the application of electromagnetic force in conventional riveting and SPR has already been investigated and shows good effect. Future research should explore whether electromagnetic force can enhance the mechanical properties of clinched joint or clinch riveting joint.

3.6 Laser-arc welding assisted riveting

Aluminum alloy is widely used in automotive structure to reduce the weight. Conventional welding cannot achieve effective joining of dissimilar material such as aluminum alloy and high strength steel due to huge thermal-physical difference between them. Riveting, which belongs to mechanical joining, has the advantage of joining dissimilar material. Yet, mechanical properties of joint produced by conventional riveting is relatively low [84] compared with welding. Thus, a hybrid method that combines riveting with laser-arc welding was invented.

The process of laser-arc welding assisted riveting (LWAR) is shown in Fig. 20. Steel sheet is placed on the top side of aluminum sheet. Drilling machine is used to drill a hole which has the same diameter as rivet diameter in the center of lap area. Steel brush is used to polish both sheets so as to remove oxide layer and surface is cleaned by ethyl alcohol. When assembling, rivet tail successively passes through aluminum alloy sheet and steel sheet from bottom to top. The length of rivet tail is equal to the sum of steel sheet thickness and aluminum alloy sheet thickness. Then, both sheets together with rivet are fixed by clamp to ensure stability. After welding process begins, laser-arc heat source points at the clearance between rivet and steel sheet all along. The plane formed by laser and TIG is tangent to the arc of rivet. Sample moves with the move of workbench in a circular motion at uniform velocity. The direction of rotation is determined by the order of laser-arc heat source. Always keep laser in the former and TIG in the latter. Welding order is controlled by welding program in the computer of heat source system, and welding

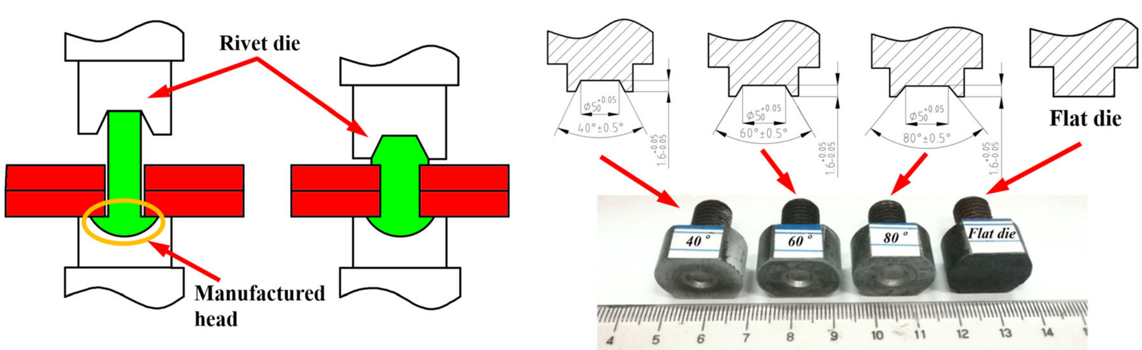


Fig. 17 (**a**) Riveting process (**b**) Riveting die with different die angle [80]

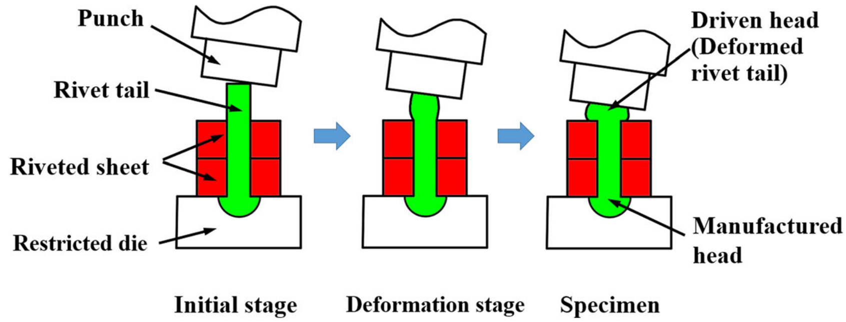


Fig. 18 Joints formed with angle deflection

process can be carried out automatically after program has been launched. Set welding time to match the time required for heat source to make one revolution round the rivet so as to obtain a complete circular welding seam.

Wang et al. [84] researched the mechanism of LWAR. The thickness of IMCs which is determined by heat input has a great effect on joint quality. The accuracy of heat input controlling can be achieved by application of laser-TIG hybrid heat source. It was found that as laser power rose, tensile strength of joint first increased and then decreased. When laser power was set to 220W, tensile strength of joint reached 6.3kN and was close to that of steel sheet. Moreover, IMCs in this situation was relatively thin and was more uniform, leading to better mechanical properties of joint. Two failure modes could be found in tensile test. One was button-type fracture; the other was pull-out fracture, as is shown in Fig. 21. When the strength of welding zone surpassed that of rivet head, joint would fail in the manner of pull-out fracture. Thus, joint whose failure mode is pull-out fracture possessed better mechanical properties. Han et al. [85] researched microstructure of LWAR joint. Outlook and cross-section of LWAR joint is shown in Fig. 22. Three load bearing regions, which were steel-steel joint (formed by steel sheet and steel rivet), steel-aluminum joint (formed by steel sheet, aluminum sheet and steel rivet), and steel-aluminum interface (formed by rivet external wall and internal wall of aluminum sheet), could be found in hybrid joint. Among them steel-steel joint bore the main load in strength test. Steel-aluminum joint was the key factor that determines mechanical properties of the whole joint since IMCs was formed in this region. The existence of steel-aluminum interface ensured the tightness of joint. They also utilized stepped rivet in LWAR. The application of stepped rivet made the region of steel-aluminum joint smaller and therefore increased the stability of joint, as is shown in Fig. 23. Besides, they found that mechanical interlock existed between aluminum alloy sheet and rivet. Effect of mechanical interlock was relevant to diameter difference between rivet head and rivet tail. Enhancing diameter difference between rivet head and rivet tail could enhance effect of mechanical interlock, thus enhancing joint strength. Wang et al. [86] established a model which is based on GA-BP neural network to predict morphology of weld in LWAR process. Aluminum rivet was used to join aluminum sheet and CFRP sheet. By inputting basic parameters of welding process, the model will predict and present final morphology of joint, making it convenient for researchers to optimize the process. Their work is basically in accordance with experiment, and offers a new means to explore energy transfer in LWAR.

LWAR proves to an effective way to join dissimilar materials. However, the cost of equipment is high, restricting its wide application in industry. Laser beam is very thin. If the assembling accuracy of workpiece cannot be ensured, laser will not point at the clearance and welded defects will appear in joint. High requirements for installing accuracy increase the complexity of joining process. Besides, process parameter such as welding current, welding speed and defocused distance will also affect quality of joint. Their effects need to be further investigated so as to get optimal parameter combination. Moreover, in all the research of LWAR, material of rivet is the same as lower sheet. Yet, other material may have better welding properties than that of identical material. Future research should test rivets of different material and shape so as to improve joint strength.

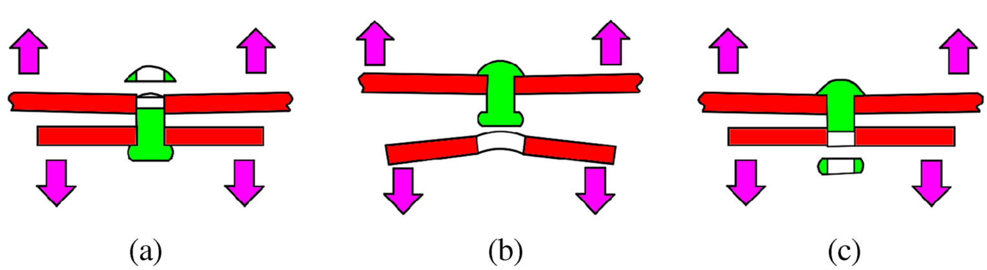


Fig. 19 Schematic of failure modes in tensile test. (a) Fail at manufactured head. (b) Driven head pullout. (c) Fail at driven head

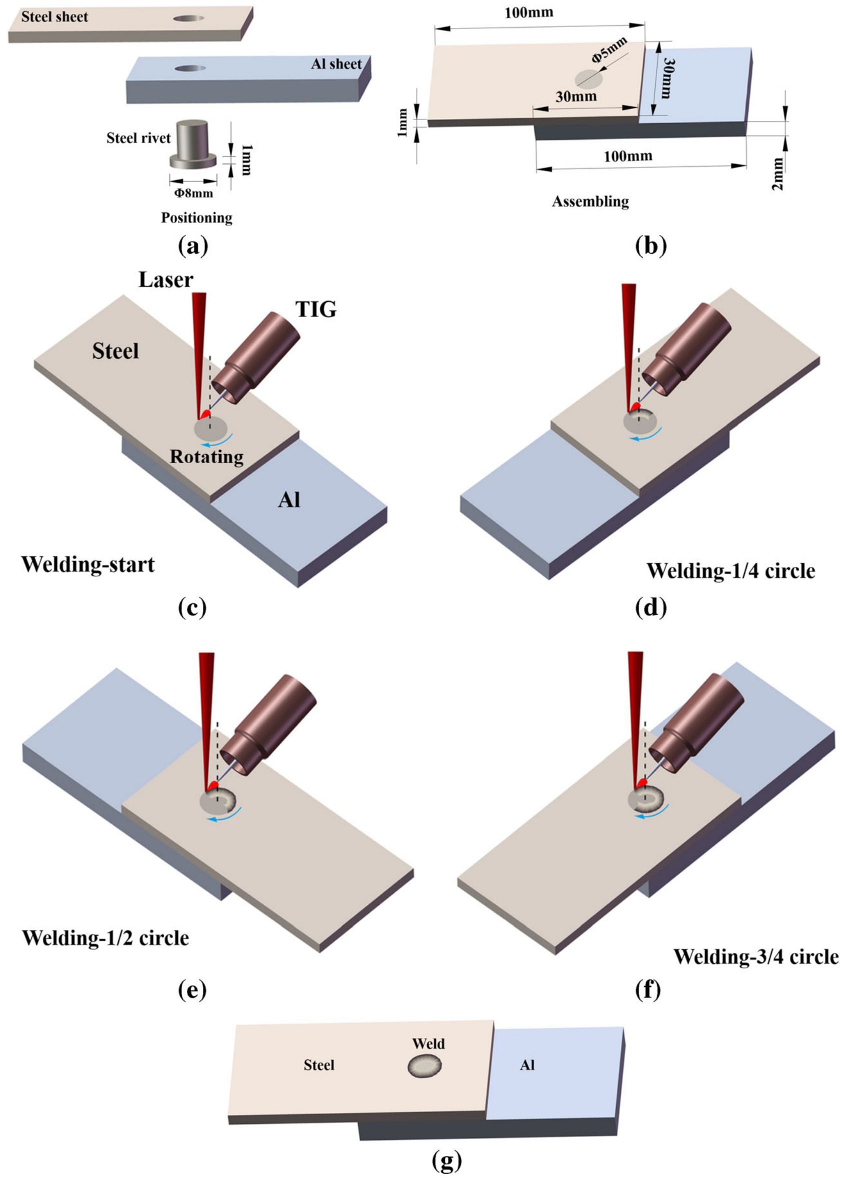


Fig. 20 (**a**), (**b**) Dimensions and assembly diagram of the welded specimen. (**c**) - (**f**) Schematic diagram of the Al/Steel welding-riveting process. (**g**) Diagram of the tensile test specimen. [84]

3.7 Resistance rivet welding

Resistance rivet welding is a joining technology that combines riveting with resistance spot welding. Process of resistance rivet welding is shown in Fig. 24. Semi-hollow rivet similar to rivet used in self-piercing riveting is used in this craft. Sheets together with rivet are placed between two electrodes. Aluminum alloy sheet is placed as upper sheet and steel sheet is placed as lower sheet. Electric current I_1 and force is applied to upper electrode. Electrical resistance heat is generated, softening sheet material. Rivet is driven by electrode to press the sheet until rivet tail reaches lower steel sheet. After that, electric current I_2 is applied to upper electrode. Rivet tail is welded to lower steel sheet along with the forming of a sphere-shaped melting zone between rivet and lower steel sheet. Thus, a welded joint is formed and upper electrode releases.

Niu et al. [64] utilize RRW to joint aluminum alloy to press hardened steels (PHS). An Al-steel blended nugget was formed by welding of trapped aluminum alloy, inside wall of rivet cavity and PHS at the border of two sheets, as is shown in Fig. 25. Two failure modes were found in shearing test of RRW joint. One was interfacial fracture (IF), the other was button pull-out fracture (BPF), as is shown in Fig. 26. Failure mode of joint was determined by strength competition between blended nugget and aluminum alloy. When nugget was small, strength of nugget was lower than that of aluminum alloy and joint strength was depend on strength of nugget. Thus, failure mode was IF. When nugget grew bigger and its strength surpassed that of aluminum alloy, joint strength was depend on strength of aluminum alloy and failure mode turned to BPF. In another article, Niu et al. [87] applied RRW in the joining of magnesium alloy and steel. Microstructure of

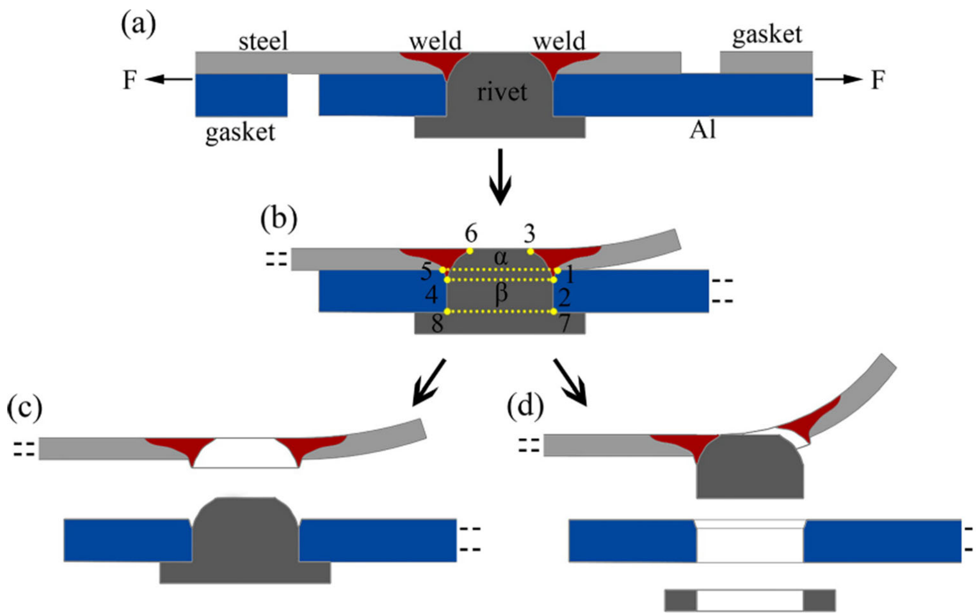


Fig. 21 Failure modes of joint. (a), (b) Process of shearing test. (c) Button-type fracture. (d) Pull-out fracture [84]

welding zone was observed by metallographic analysis. It was found that magnesium alloy was not welded to steel on account of their low mutual solubility, as is shown in Fig. 27. Steel rivet was welded to steel sheet and formed a nugget. The joining of magnesium alloy and steel was depended on the nugget, and the nugget was constituted of lath-like martensite.

Joint produced by RRW has high strength and is reliable. However, the requirement for coaxial degree between rivet and electrode is high, increasing the complexity of the process. Besides, there is no effective way to evaluate the joint quality without destroying it. In order to obtain joint with better mechanical properties, the effects of forming force, welding current and rivet shape need to be further researched. Moreover, martensite in the nugget will lower the tenacity of joint. Therefore, fatigue strength of joint should be investigated and improvement measures should be proposed.

3.8 Friction riveting

With the increasing application of composite material in aviation industry, the joining of composite material to alloy brings problems to researchers. Borba et al. [88] investigated friction riveting of composite material in aircraft structure. The joining procedure of friction riveting [89–92] is shown in Fig. 28. Two components are fixed by clamp and metallic rivet is placed in the spindle. After that, rivet begins to rotate and moves towards the upper component. Frictional heat generated by the combined effect of rotation and axial force forms a thin layer of molten composite around rivet tail. Metallic rivets continue to moves down and inserts into lower composite, making part of molten material squeezed out. Local temperature near the rivet tail increases significantly due to low thermal conductivity of composite materials. Then, rivet stops rotating and an axial force is applied to the rivet. Material below the rivet tail is compressed. Rivet tail is forged by counterforce of material, forming a structure in the shape of a mushroom. After forming, axial force is released and local temperature around rivet tail cools down. Then, the joint consolidates, firmly joining two sheets.

Altmeyer et al. [89] investigated influence of various parameters on joint quality. Four process parameters including rotational velocity, friction duration, friction force, and forming force were researched and a design of experiment was conducted to figure out their effect on joint forming. Tensile strength was regarded as criteria to evaluate mechanical properties of joint. X-ray scanning was carried out before tensile test so as to explore the relationship between geometry

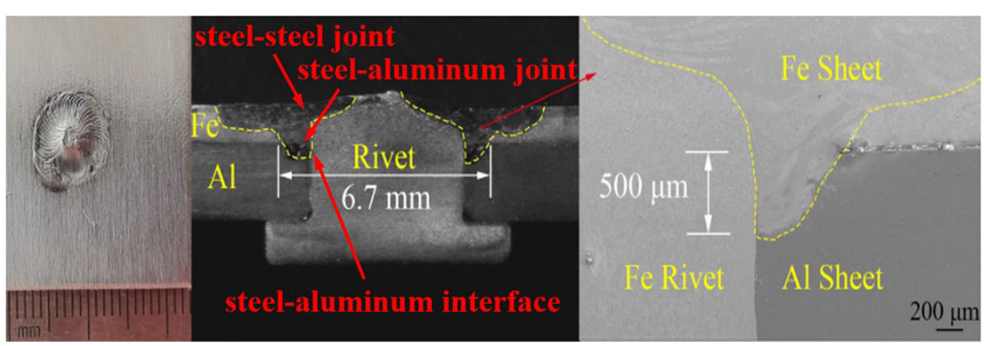


Fig. 22 Outlook and cross-section of LWAR joint [84]

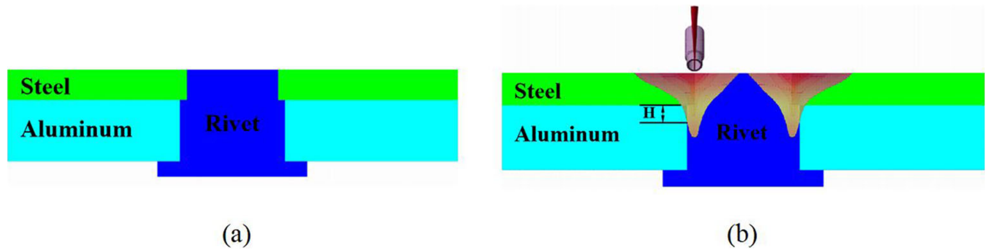


Fig. 23 Schematic of the application of stepped rivet. (a) Assembly structure. (b) Thermal distribution of joint

of rivet tip and joint strength. It was found the larger rivet tip diameter, the higher the joint tensile strength. Rivet tip diameter would increase with the increase of rotational velocity, friction duration and forming force. The strength of joint would be the same as that of base material when diameter of rivet tip expanded 70%. In the meantime, failure mode of joint would change from rivet pullout to rivet fracture, as is shown in Fig. 29. Variance analysis as well as a regression equation, which has a high degree of accuracy to predict mechanical properties of joint, had been used to optimize process parameters. Borges et al. [93] established a finite element analysis model to further assist optimization design. Borba et al. [94] compared mechanical properties of friction-riveted joint with that of bolting joint by experiments. Results showed that friction-riveted joint had a lower quasi-static shearing strength but a much higher fatigue life. The reason was that material which were squeezed into the gap between two sheets in forming process would act as adhesive to fasten two sheets. Clearance at the interface between rivet and sheets was eliminated compared with bolted structure. Besides, when conducting fatigue test, crack propagation was mainly arrested by rivet which deforms plastically. Borba et al. [90] also investigated corrosion behavior of friction-riveted joint. It was found that mechanical properties of joint actually increased 23% rather than decreased after being exposed to high temperature and high humidity environment for 28 days. The reason was that matrix was driven by temperature and water uptake to crystallize on fiber surface, resulting in composite strengthening in the surrounding area of rivet.

Since the joining is achieved between rivet and lower sheet, there are threads on upper part of rivet and an additional nut is needed to be installed on rivet to fasten two sheets. Rivets of other shape should be investigated so as to avoid using nut and reduce weight. Besides, interlock formed by rivet upsetting determines the strength of joint. In order to enhance joint quality, process parameters that affects rivet upsetting should be further researched.

3.9 Friction stir blind riveting

Blind riveting has the advantage of high mechanical properties and ability to joining sheets from one side. However, a predrilled hole is needed in the craft of blind riveting. Prefabricated hole will lead to long processing cycle and complexity of craft. Besides, redundancy such as burrs produced when processing hole will eliminate reliability of structure. Wang et al. [95–97] invented friction stir blind riveting, which combines blind riveting and friction stir riveting. The principle of friction stir blind riveting is shown in Fig. 30. Rivet rotates at high speed and moves towards sheets. An additional axial force is applied to rivet stem after lower surface of rivet stem reaches upper surface of upper sheet. Frictional heat, which is generated [98] under combination effect of rotational torque and axial force, softens the sheet material and thus reduce the force for rivet to penetrate sheets. Rivet driven by axial force continues to rotate and inset into sheets until lower surface of rivet head reaches upper surface of upper sheet. Then, rivet stem is pulled upward. Rivet body is squeezed and deformed by pulling of rivet stem, thus forming a mechanical interlock [99–101]. When the load reaches preset value, rivet stem is broken at the notch, with lower part of rivet stem remaining in rivet body.

Ma et al. [102, 103] researched influence of rotation speed as well as feeding velocity on joint quality. Result showed that high rotation speed as well as feeding velocity would lead to large heat input. Sheets would be sufficiently softened by heat

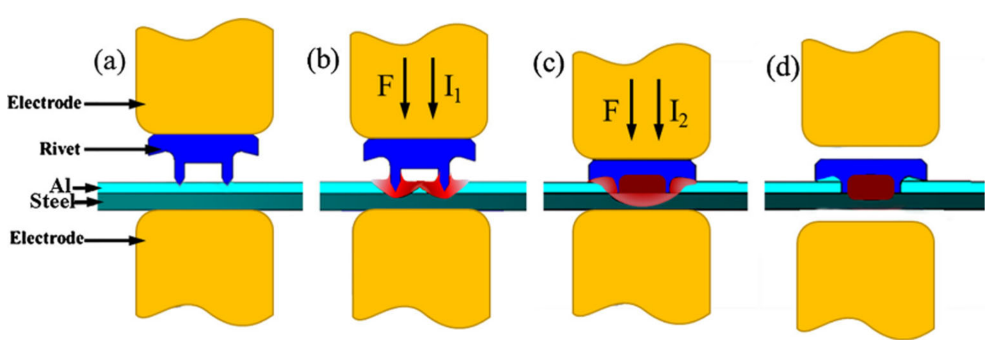


Fig. 24 Principle of resistance rivet welding [64]. (a) Positioning phase. (b) Piercing phase. (c) Welding phase. (d) Releasing phase

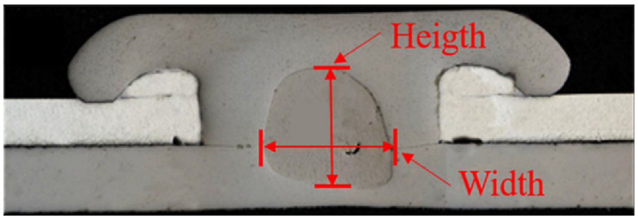


Fig. 25 Microstructure of aluminum/steel RRW joint [64]

and thus a joint with better mechanical properties was formed. They also found that location of remaining rivet stem with respect to rivet body played a decisive role in strength and failure mode of joint. It was found that when upper surface of rivet stem was lower than interface of two sheets, joint failed due to shear failure of rivet body. Thus, tensile strength, shearing strength, and energy absorption of joint were relatively low. When upper surface of rivet stem was higher that interface of two sheets, it was hard for rivet body to fracture under the support of rivet stem. Joint failed in the form of pulling out of rivet body, with substantially increase in strength and energy absorption.

Min et al. [100] utilized FSBR to join aluminum alloy sheet and composite sheet. Joints with different disposal modes presented different mechanical properties. This was determined by huge difference between CFRP and aluminum alloy in both mechanical and thermal properties. The range of parameter was narrowest in joint with both sheets being CFRP. When CFRP were placed as upper sheet and aluminum alloy was placed as lower sheet, the range of parameter was widest and failure mode of joint was shearing of lower sheet. Since joint strength was high and shearing of aluminum alloy sheet would happen before rivet being pulled out from aluminum alloy sheet. In order to further understand the mechanism of FSBR, Wang et al. [104] established a finite element model to simulate the process. Energy conversion had been investigated so as to research the effect of stirring. Results showed that

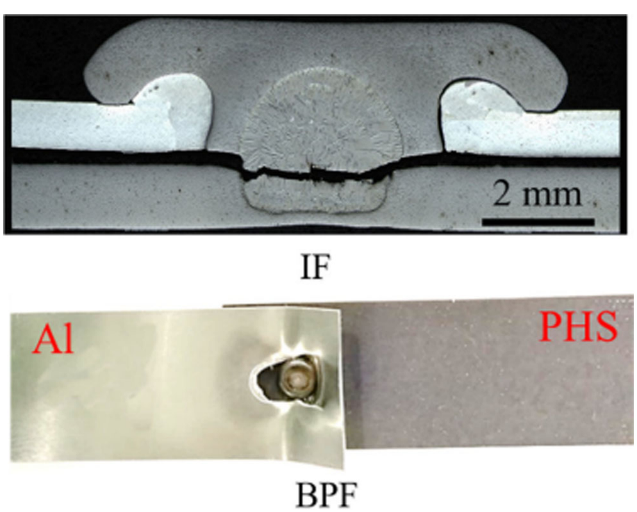


Fig. 26 Failure mode of RRW joint [64]

frictional heat produced by rotation consumed most of the energy input. While heat produced by deformation of sheets can be neglected. Li et al. [105] investigated corrosion behavior of Mg/CFRP and CFRP/Al FSBR joints. Joints were exposed to marine environment for 6 months. It was found that corrosion on Mg/CFRP joint was uniform and severe, but deep inside the gap between two sheets, the degree of corrosion was small. In the contrary, the corrosion degree was small on outer surface of CFRP/Al joint, while severe corrosion could be found deep inside the gap due to galvanic and crevice corrosion. Detached rivets of both joints are shown in Fig. 31. It was found that rivet cap of CFRP/Al joint and protrusions of both joints were corroded, while rivet cap of Mg/CFRP joint was cathodically protected due to direct contact of magnesium and rivet. Middle part of galvanized steel rivets remained pristine after exposure, indicating that the effect of rivet on crevice corrosion could be neglected. This was because rivets and crevice were not joined by electrolyte. Further research on corrosion behavior of joint is needed so as to improve the duration of joint.

FSBR combines the advantages of one-side joining and no requirement for predrilled hole. When joining, it is rivet stem that contacts sheets first. Lower part of rivet stem can be designed as sharp structure so as to reduce piercing force. Different rivet shape should be investigated to optimize the process. Besides, swarf produced when piercing remains in clearance between sheets, which will affects joint strength. Future research should be conducted to lessen the swarf and reduce the clearance.

3.10 Friction self-piercing riveting

Self-piercing riveting achieves mechanical joining by massive plastic deformation and is the most widely used technique in the joining of light weight material. However, the application of ultra-high strength material and low ductility material brings insurmountable challenge to self-piercing riveting. A hybrid method that combines self-piercing riveting and friction stir welding is thus invented, uniting the advantage of both solid phase welding and mechanical joining. Principle of friction self-piercing riveting (FSPR) is shown in Fig. 32. Spindle drives semi-hollow rivet to rotate and feed towards upper sheet. Friction begins when rivet tail contacts upper surface of upper sheet. Frictional heat produced by rotation and feeding softens sheet material, generating local plasticizing flow. With the increase of frictional time, rivet also begins to soften. Under the combination effect of metal plastic flowing and high temperature, intermetallic compound will appear in the welding area. Rivet tail bends and expands under the effect of die, forming a mechanical interlock. When rivet reaches preset position, a sudden stop of rotation is carried out on rivet. The sudden stop of rivet is a key factor that affects joint quality. So controlling deceleration time of rotation is of

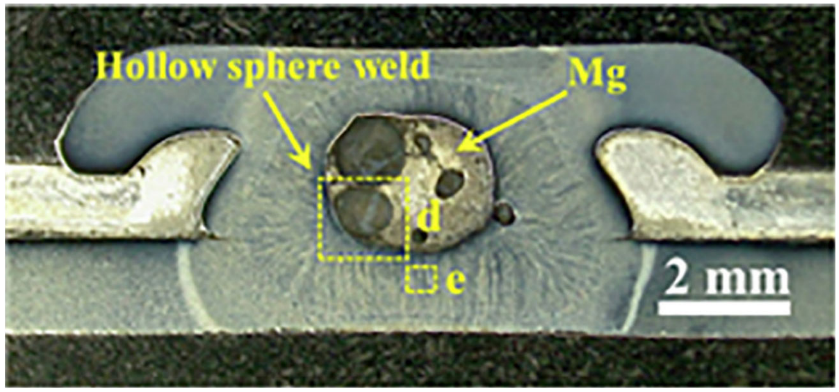


Fig. 27 Microstructure of magnesium/steel RRW joint [87]

great importance. Then, spindle separates from rivet. After joint cools down, a solid-state bonding is formed, joining two sheets with the help of mechanical interlock.

Liu et al. [107] investigated the influence of various process parameters on joint quality. It was found that high rotating speed and low feeding velocity would lead to decline in torque as well as forming force, thus resulted in decline in undercut thickness. The speed of sudden stop also has important effect on joint quality. It is mainly determined by deceleration of riveting equipment. Results showed that the faster the spindle stopped, the less likely the joint would become loose. This was because sheet material in melting condition would stick to surface of rivet, thus restricting circular loose of rivet. Ma et al. [108] utilized FSPR to joint aluminum alloy sheets. They found that compared with conventional SPR, FSPR could effectively reduce tooling force and restrain the appearance of crack. However, this resulted in less expanding of rivet tail, thus reducing mechanical interlock between rivet and lower sheet. In another article, Ma et al. [109] proposed a two-steps method to solve this problem. In softening step, rivet rotated at high speed and fed at low speed. It sufficiently softened the sheets with low ductility and effectively avoided the forming of crack. In feeding step, rivet stopped to rotate and fed at high speed, shunning excessive accumulation of heat around the rivet. Forming force is thus enhanced along with the increase of undercut thickness. Besides, Ma et al. [106] also studied the microstructural evolution in FSPR. Electron backscatter diffraction was utilized to observe the microstructure, as is shown in Fig. 33. Massive deformation of sheets as well as local temperature rise in riveting process produced complicated and multiphase microstructure. Two fine grain zones (FGZs) were formed by grain recrystallization of sheet material near the rivet. One was in the area that surrounded the rivet; the other was in the cavity of the rivet. Solid-state joining between upper sheet and lower sheet was formed outside the rivet, and solid-state joining of trapped aluminum was formed inside the rivet. Ma el al. [110] also studied the effect of switch depth on joint strength. It was found as switch depth declined, hardness of joint increased and failure mode of joint changed from rivet pullout to upper sheet fracture, as is shown in Fig. 34. This was because joint strength increased due to larger flaring of rivet tail. Increasing in hardness compensated for the sheet softening effect caused by frictional heat, presenting a higher overall hardness than SPR joint.

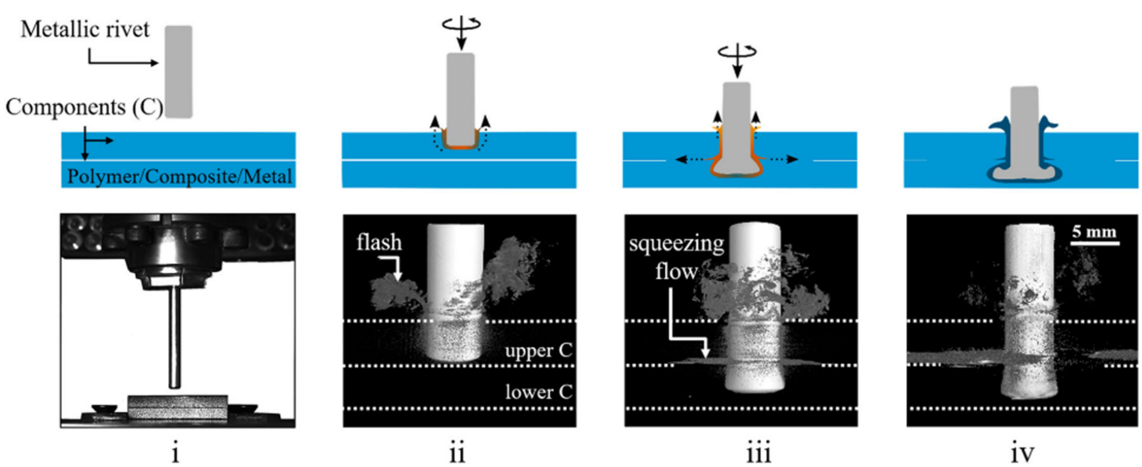


Fig. 28 Process of friction riveting. (i) Positioning stage. (ii) Melting stage. (iii) Inserting stage. (iv) Consolidation stage [88]

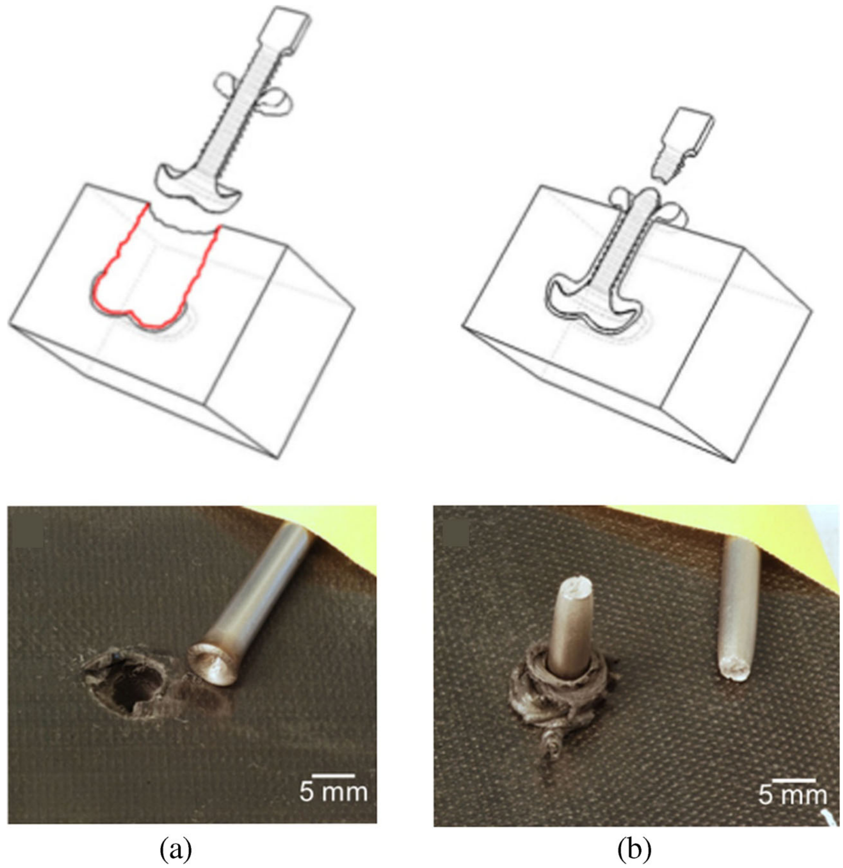


Fig. 29 Schematic and photo of joint failure mode. (a) Rivet pull-out. (b) Rivet fracture [89]

The use of semi-tubular rivet reduces the size and weight of joint. Semi-hollow structure in the rivet can contain part of material and lessens the local deformation of joint. However, frictional heat generated in the joining process not only melts the sheet material, but melts the rivet material as well. Melting degree of rivet may be more severe than that of sheet, thus preventing rivet tail from piercing upper sheet. In order to avoid this situation, the matching of rotational parameters and rivet material need to be further investigated.

3.11 Friction element welding

Friction element welding is a hybrid joining technology that combines riveting with friction spot welding [111–114]. The principle of friction element welding, which is converting direct joining between dissimilar material into joining homogeneous material, is similar to that of resistance element welding [115] and laser-arc welding assisted riveting [84, 86]. Process of friction element welding is shown in Fig. 35. Aluminum alloy sheet is placed as upper sheet while steel sheet is placed

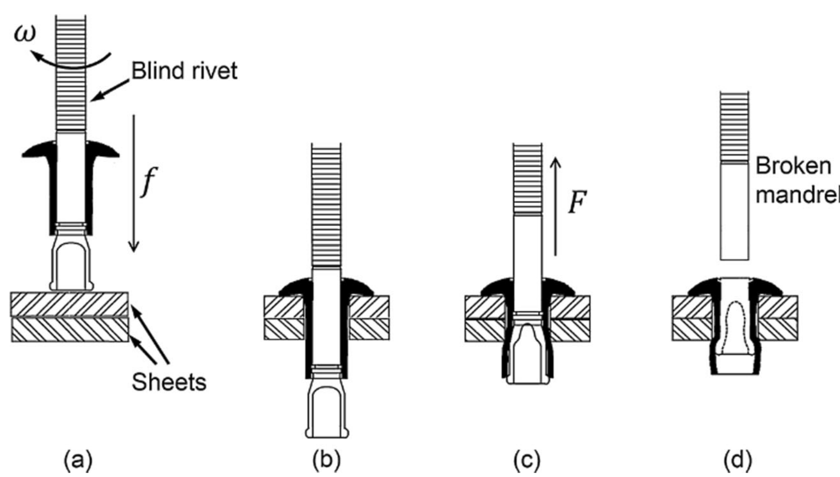


Fig. 30 Principle of friction stir blind riveting [32]

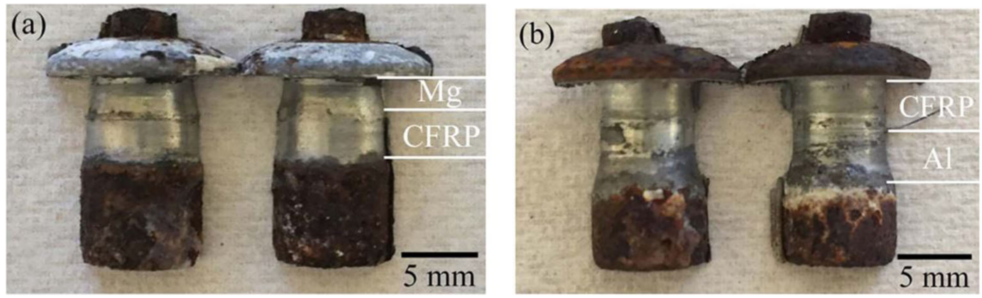


Fig. 31 Detached rivet of (a) Mg/CFRP joint and (b) Al/CFRP joint [105]

as lower sheet. Solid steel rivet with material being same kind as lower sheet is placed on the surface of aluminum alloy sheet. Rivet rotates at high speed and moves down. Frictional heat produced in the process softens aluminum alloy sheet so as to improve its liquidity. With rivet feeding downward and penetrating upper sheet, material of upper sheet is squeezed out and flows into groove under the rivet head. After lower surface of rivet contacts upper surface of steel sheet, upsetting and plastic deformation occur on the rivet under the combination effect of frictional heat and axial force, increasing contact area between rivet and steel sheet. After preset feeding depth and energy input is reached, rivet stops rotating while driving head keeps pressure. A solid phase joining is formed between rivet and lower steel sheet after joint cools down, locking aluminum alloy sheet between rivet head and lower steel sheet, thus achieving indirect joining between aluminum and steel.

Jamie et al. [112] conducted a design of experiment to explore the influence of force, rotational speed and distance on joint quality. They found that the effect of these parameters in cleaning step was the greatest. The aim of cleaning step was to remove coating on the surface of lower steel sheet and preheat lower sheet for the upcoming welding step. It was found that increasing the force in cleaning step resulted in decline in energy consumption and process time. Diameter of welding area increased with the increase of rotational speed as well as force in welding step. Hardness of material in welding area was tested by micro-hardness measurement and presented a raised value. Ruszkiewicz et al. [113] wanted to produce strong joint with least process time by changing process parameters. Research showed that process duration can be decreased by a maximum of 39% with minor decline in mechanical properties of joint. Absara et al. [114] placed micro thin film thermocouples at the interface between two sheets so as to monitor temperature evolution in welding process. It was found that highest value of temperature appeared in cleaning and welding process. Data collected in experiment also set the foundation for further research on microstructure of welding area. Varma et al. [111] established a finite element model to simulate the process. It was found deformation of rivet happened in cleaning step and temperature of rivet was much higher than that of sheet material. Accuracy of simulation can be further verified by temperature measurement.

Friction element welding can effectively join materials of different kinds. Yet, there are still some problems. Equipment is adapted from milling machine and cost is high, limiting its wide application in industry. A groove must be designed at rivet head to contain material which has been squeezed, enlarging the size of rivet and increasing its weight. Improvement measures of rivet shape should be proposed in future research. Besides, welding of rivet and upper sheet has not been studied in depth. Though this is not the area that bears the main load, it also affects the strength of joint. Welding properties of this part need further investigation.

3.12 Flow drill screwing

Flow drill screwing (FDS), also known as self-drilling screwing, is widely used in the joining between sheets and hollow or semi-hollow structure. Schematic diagram and

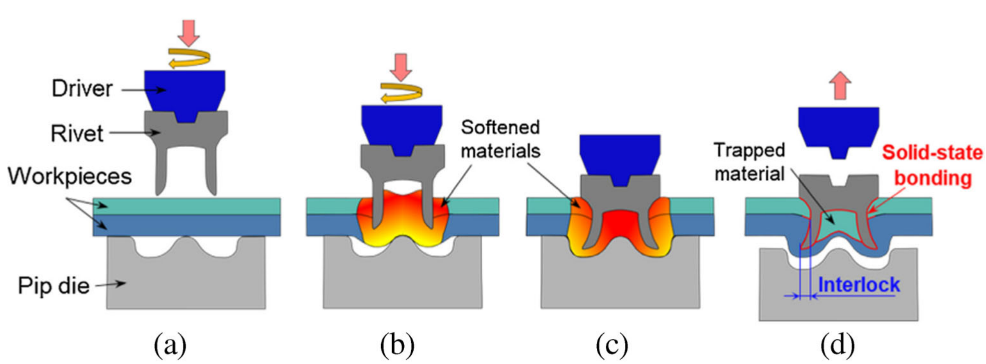


Fig. 32 Process of friction self-piercing riveting. (a) Positioning. (b) Softening. (c) Forming. (d) Releasing [106]

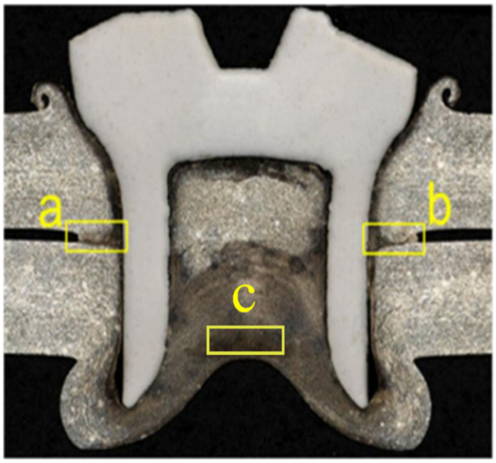
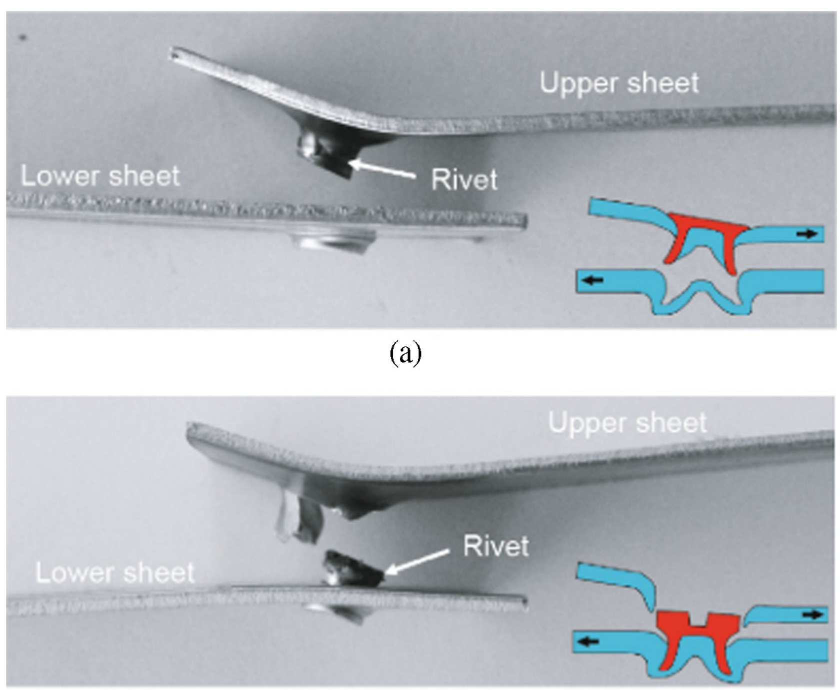


Fig. 33 Microstructure of FSPR joint. (a), (b) Sheet-sheet interface outside the rivet. (c) Fine grains inside the rivet cavity [106]

cross-section of joint is shown in Fig. 36. In the process, bolt is driven by driving head rotating at high speed to pierce the sheets to be joined. Frictional heat produced under the combination effect of rotation and downward pressure softens the sheet material and generates local plastic flow in sheet material. A joining area with thickness larger that total thickness of two sheets is formed. Finally sheets are joined by thread meshing between outer thread of bolt and inner thread of sheet hole.

Compared with other riveting techniques, FDS has many advantages. Sheet joining can be completed from one side, lowering the requirement for joining space. Thus, it is suitable to join sheet to tubular or close structure. Joint produced by FDS is removable, thus unqualified joining can be replaced with a larger diameter screw for repair. Besides, adhesive bonding can be combined to FDS to achieve joining of dissimilar material.

Nagel et al. [103, 117] utilized FDS to join CFRP sheet and aluminum alloy sheet. CFRP sheet was placed as upper sheet and aluminum alloy sheet was placed as lower sheet. It was found that resin fragment which was cut off from upper CFRP sheet remained in the clearance between screw and aluminum alloy sheet. Thus, perfect thread meshing between screw and sheet cannot be achieved, seriously affecting mechanical properties of joint [103, 117]. Huang et al. [103, 118] investigated the effect of predrilled hole upon mechanical properties of joint. It was found that in joint without a predrilled hole on upper sheet, aluminum alloy would be squeezed by screw and flowed into the gap between two sheets. Thus, clearance would be formed between two sheets in the final joint. Process of FDS with a predrilled hole on upper sheet [103, 118–120] is shown in Fig. 37. Predrill hole eliminated clearance between two sheets and greatly improved tensile and shearing strength of joint. Johan et al. [121] also researched flow-drill screwing with a predrilled hole. They conducted component test on single-hat specimen. Geometry of specimen is shown in Fig. 38 and failure modes of joints are shown in Fig. 39. Four failure and deformation modes of joints, which were screw rotation, screw pullout, screw push out, and screw fracture, were found in component test. It was found that force in component test was 15–20% higher than that of quasi-static tests. The rising of absorption energy was attributed to the appearance of lateral inertia forces in the



(a)

(b)

Fig. 34 Failure mode of FSPR joint in shearing test. (a) Rivet pullout. (b) Upper sheet fracture [110]

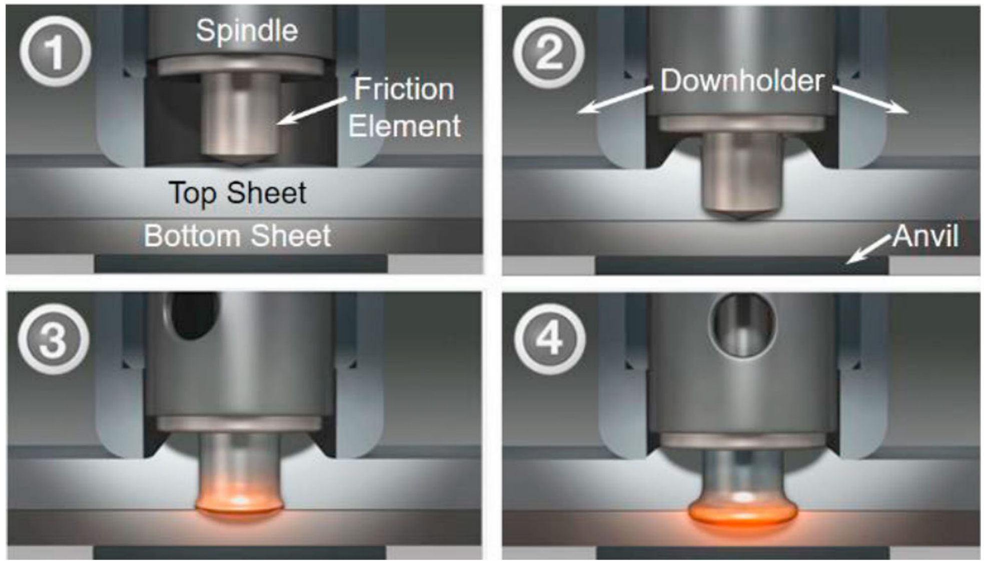


Fig. 35 Forming process of friction element welding. (i) Penetration. (ii) Cleaning. (iii) Welding. (iv) Compression [114]

profile during progressive folding. Pan et al.[120] researched the effect of sheet thickness on shearing and fatigue performance of joint. It was found that as sheet thickness rose, shearing failure of joint changed from screw head penetration to screw fracture. Fatigue failure will change from lower sheet fracture to upper sheet fracture.

Despite the convenience of FDS, there are also some disadvantages. Clearance between screw and lower sheet makes it easy for corrosive medium to enter, thus pose electrochemical corrosion problems to joint. Therefore, corrosion behavior of FDS joint needs to be investigated and precautionary measures should be proposed. Long tip protuberant part of screw produced after piercing of lower sheet will restrict its application in compact structure. If the sheets to be joined are too thin, the part of sheets which is in contact with screw may only have one or two turns of thread, resulting in relatively low tensile strength of joint. Relatively heavy weight and high cost also prevent it from being extensively used. Future work should focus on minimizing the size of screw so as to reach the same strength while using the least material.

3.13 Rivtac

High speed bolt joining (rivtac) is a new joining technology that is used in the production and manufacture of car body. It has attracted more and more attention among researchers in recent years. It was first used by Daimler corporation in the construction of Mercedes-Benz car body [122, 123]. The principle of joining process is shown in Fig. 40. Bolt, as a joining assisting component, has a similar effect to rivet in this technique. Pneumatic piston drives bolt and inserts it into workpiece at a speed of 20-40 m/s. Workpiece will not be severely deformed due to high speed and short time. Besides, local temperature rises under the combination effect of high deformation rate and frictional heat produced between bolt and workpiece, improving the fluidity of metal workpiece. Thus, this method is suitable to be applied in the joining of high strength material. The using of profiled shaft enables bolt to be firmly anchored in sheet by thread fit. Besides, joining area around the bolt will deform elastically due to punch of bolt. Therefore, interference fit is achieved and a radial force will be

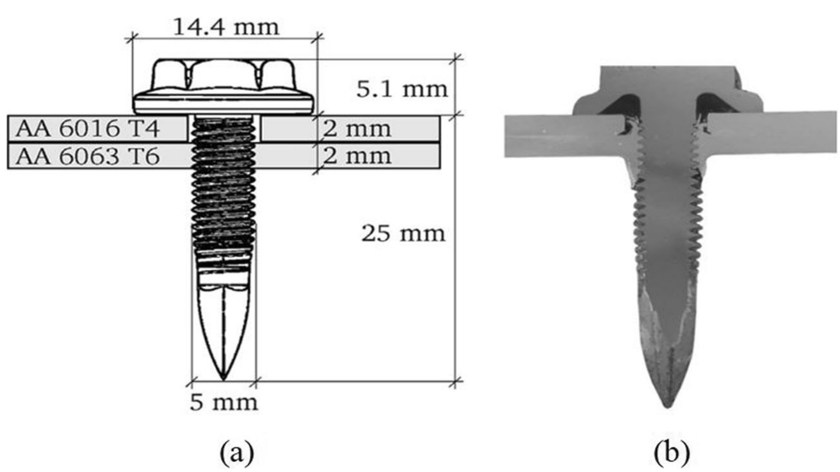


Fig. 36 (a) Schematic diagram. (b) Cross-section of FDS joint [116]

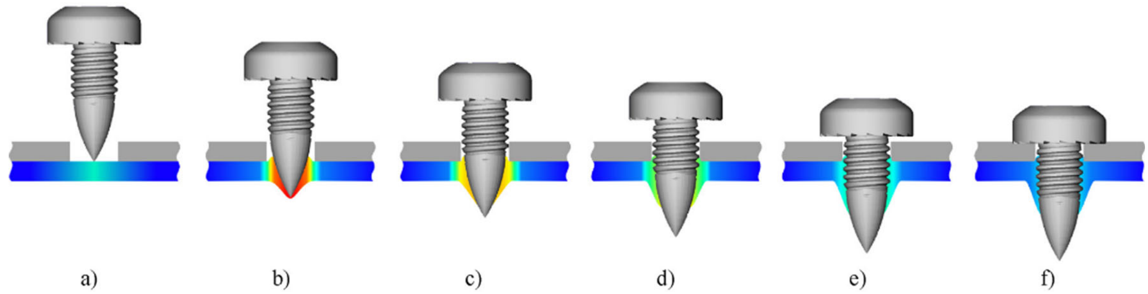


Fig. 37 Schematic of FDS with a predrill hole on upper sheet [121]

applied by sheet material around the bolt to fasten the bolt. High speed means force exerted on bolt is intense. If material of bolt is too brittle, micro-cracks will appear at profiled shaft, thus significantly reducing strength of joint. Meschut et al. [123, 124] adopted high speed bolt joining to join 6061 aluminum alloy sheet and 22MnB5 high strength steel sheet. The thickness of both sheets was 2 mm. Effective joining can be achieved, with joint strength reaching 6.86 kN. Kim et al. [125] compared rivtac with FDS and found the strength of rivtac joint is about 30% lower than that of FDS joint. Two failure modes, plate failure and fastener failure were found in strength test of rivtac joint. They also established an artificial neural network model to predict the load displacement curves of rivtac joints. The model exhibited errors within 11.1 %, indicating that their work is highly consistent with experiment results. Meschut et al. [126] conducted numerical simulation on the process of rivtac. They found that setting for remeshing plays an important role in the accuracy of simulation. This is caused by the complexity of coupled structural-thermal simulation, so the frequency of remeshing needs to be carefully selected. Ufferman et al. [127] combined adhesive bonding with rivtac. It was found that strength of hybrid joint was determined by strength of adhesive, while energy absorption was greatly improved by rivtac.

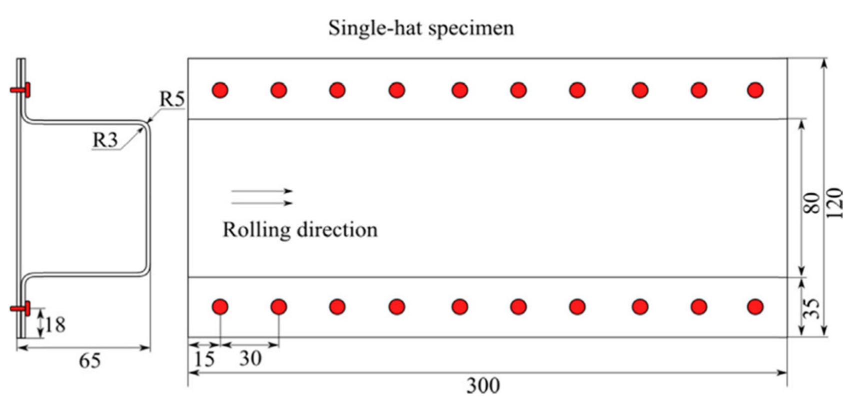
4 Future trend

With more and more people realizing the importance of environmental protection, light weight structure, which can greatly reduce energy consumption, is bound to be a mainstream in manufacture. For aviation and aerospace industry, light weight means lower fuel consumption, higher carrying capacity, longer range, more flexible mobility, and lower carbon emission [103]. Demand of huge increase in carrying capacity and effective range puts forward higher requirement to light weight structure. The wide application of light weight material is inevitable in the near future due to its low density and high mechanical properties. Riveting, which plays an important role in the joining of light weight material, will still develop rapidly. Some future trends of riveting techniques are listed below to help readers to further research.

4.1 Innovative forming method

Several riveting techniques reviewed in this article are invented by innovative design on conventional craft. Reshaped riveting and restored riveting originate from mechanical clinching. An additional step was implemented so as to increase joint neck thickness. Thus, mechanical properties of joint are greatly improved. Clinch riveting originates from self-piercing riveting. Contrary to self-piercing riveting, upper sheet is not pierced. So it possesses higher corrosion resistance. It can be concluded that mechanical properties of joint can be greatly improved by modified method from existing techniques. Additional element or step, material, geometrical parameters of forming tools are the common orientations that are investigated by researchers in innovative design. With the advance of information technology, researchers can conduct simulated experiment in computer by using finite

Fig. 38 Geometry of single-hat specimen [121]



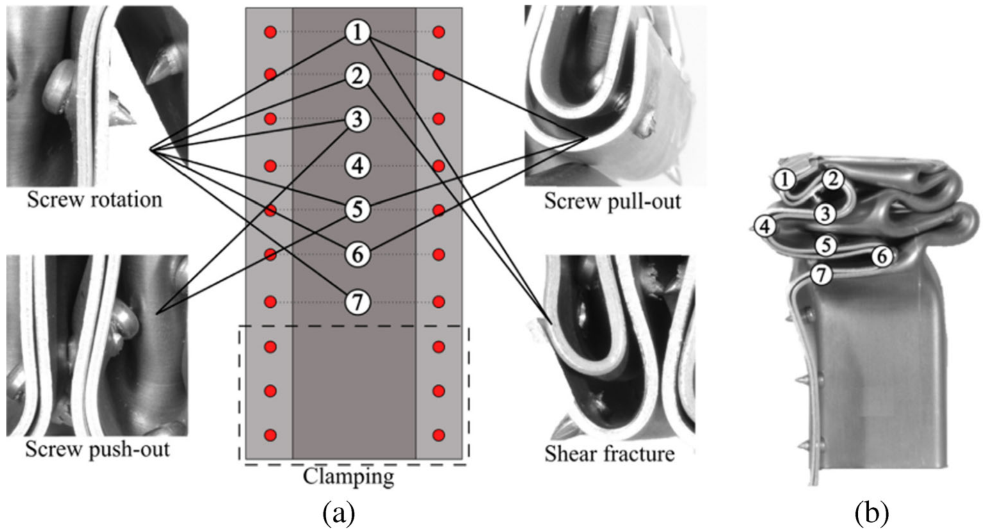


Fig. 39 (a) Failure modes of joints with different location. (b) Position of screws after crushing [121]

element software when they come up with innovative idea. This will greatly reduce cycle and cost of research. Due to the resonance and stress variation during the flight, conventional riveting which has interference fit will still be the first choice for aircraft structure. However, the craft of predrilled hole will greatly lower the assembly efficiency and automation degree. Developing novel riveting technology which has low forming force and does not need predrilled hole is an important orientation for aviation. [103]

4.2 Application of special energy field

Special energy fields such as electromagnetic field, laser and ultrasonic play important role in high-end manufacturing. The application of electromagnetic field and laser in riveting has already been discussed in this article. Many researches have already been done on electromagnetic riveting. However, there are relatively few researches on application of laser in riveting and there is virtually no research on ultrasonic riveting. Though application of special energy field will increase the cost compared with conventional riveting, it will produce joint with much better mechanical properties. Ultrasonic is a mechanical wave that can transmit high energy. Ultrasonic vibration can greatly reduce forming force of material and enhance material flow. Besides, it will reduce friction between workpiece and die, and thus enhance mechanical properties of material and joint. However, the physical mechanism of ultrasonic vibration has not been studied in depth and previous studies only focus on simple experiments. Further research on ultrasonic vibration assist riveting needs to be conducted and is worth expecting.

4.3 Combination of riveting and welding

Both welding and riveting are typical joining technologies. Many welding techniques, such as laser-arc welding, friction spot welding and resistance spot welding have already been combined to riveting and are discussed in this article. Joining

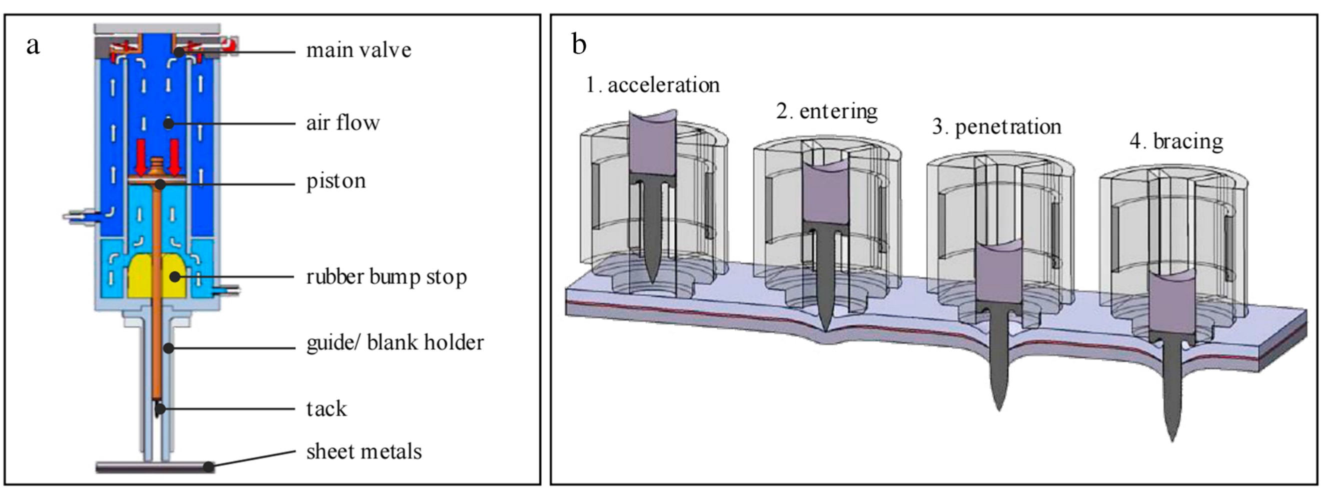


Fig. 40 (a) Equipment of rivtac. (b) Schematic of high speed bot joining process [126]

of material with ultra-high strength and low ductility is still a big challenge for riveting. Frictional and joule heat is introduced by hybrid method to solve this problem. Compared with riveting, welding has higher static strength and lower fatigue strength. Welding between dissimilar materials, especially materials with huge difference in physical and thermal properties, is a hot topic of current research. Hybrid joining combines the advantages of both and is an important development orientation for joining techniques.

4.4 Optimization by finite element simulation

Research on effect of various process parameters on joint quality is necessary in any king of riveting. In the past time, this process is completed by experiment and experience. However, experiment has the defects of high cost and low design efficiency. Due to the fast development of information technology, finite element analysis software such as Abaqus was invented to assist design. Forming process of riveting can be simulated in computer and many details which cannot be seen in experiment can be observed by simulation. Strength test such as tensile test and shearing test can be carried out in simulation so as to predict mechanical properties of joint. Researchers can conduct a large amount of simulation to obtain correlation between mechanical properties and input parameters. Then, advanced algorithms such as genetic algorithm and neural network algorithm can be used to optimize the parameters and get optimal combination. Despite all this advantages, there are also some problems that need to be solved. Accuracy of simulation result is affected by many factors such as material properties, meshing quality, friction coefficient and so on. Parameter such as friction coefficient will change in forming process and thus is hard to measure. Even simulation prediction of mechanical joining like self-piercing riveting cannot achieve high degree of accuracy due to complexity of joint fracture. Let alone simulation of hybrid joining whose process is more complicated than that of self-piercing riveting. In order to establish more accurate models, forming mechanism of riveting should be further researched.

5 Summary

Various riveting techniques have been reviewed in this article. Principle of each craft has been introduced. It can be seen that most novel riveting techniques mentioned above can be divided into two categories, modified method originated from existing riveting and hybrid method which combines riveting with other joining techniques. Process parameters that affect mechanical properties of riveting joint are analyzed and discussed. For riveting which belongs to mechanical joining, material and geometrical parameters of forming tool are usually main factors that determines joint quality. For hybrid joining, process parameters that affect welding quality can also affect quality of hybrid joint.

Latest research on different riveting techniques has been listed. Advantages and disadvantages of each technique have been introduced. Self-piercing riveting can achieve high strength as well as high degree of automation and will still plays a dominating role in joining light alloy and dissimilar material. Clinch riveting has high assembly efficiency and possesses higher corrosion resistance compared with self-piercing riveting. It will be an alternative joining technique to self-piercing riveting in certain circumstances. Friction riveting and friction stir blind riveting achieves one-side joining and joining without predrilled hole by introducing frictional heat. This will give them huge advantages in joining tubular or close structure. Reshaped riveting presents a solution to improve mechanical properties of clinched joint. Restored riveting offers a choice to restore damaged clinched joint so as to avoid material waste. Electromagnetic riveting deforms rivet uniformly due to its high speed and large impact. Thus, it is suitable to join composite material and titanium alloy, which has a wide application in aviation and aerospace industry and is difficult to be joined by conventional riveting. Flow drill screwing and rivtac has the advantage of simple processing. Yet, it can only be used in the joining of sheet and hollow structure. Both friction element welding and laser-arc welding assisted riveting convert the joining of dissimilar material to the joining of identical material. They combine the advantage of mechanical joining with that of solid phase joining and avoid direct welding of materials with rather different physical properties. The principles of the two techniques are similar. Resistance rivet welding provides an optional method to weld immiscible materials such as magnesium and steel by inducing joule heat. It can be concluded that each craft has its own features and can be applied to respective fields.

Code availability Not applicable.

Author contribution Chao Chen, Jinliang Wu, and Denglin Qin analyzed the data; Chao Chen, Jinliang Wu, and Haijun Li contributed reagents/materials/analysis tools; Chao Chen, Jinliang Wu, and Yawen Ouyang wrote the paper.

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Data availability The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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