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ORIGINAL ARTICLE

Clinching process for joining dissimilar materials: state of the art

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Abstract Clinching is a method for mechanically joining sheet metal of different thickness and properties in which the two plates to be joined undergo plastic deformation. The clinching process is established by connection or joining using simple tools: a punch and a die. This method has different characteristics compared to thermal joining methods, such as spot welding, including low purchase and operating costs, little preparatory work, safe and environmentally friendly, interesting mechanical properties, reproducibility, and durability. In this article, a brief review of traditional joining methods for dissimilar materials and the clinching process are illustrated in greater detail. In addition, the article looks to guide researchers for future work by identifying weaknesses of the current processes as well as potential for valuable contributions in the field of clinching.

Keywords Mechanical methods · Clinching · Welding · Metal forming · Resistance spot welding · Review

1 Introduction

Joining dissimilar materials, such as aluminum and steel, is practiced in various industries from automotive, railway vehicle, and truck manufacturing to computer and furniture fabrication. Demand from so many industries both creates a greater range of new requirements and makes those requirements ever more demanding and stringent. Weight reduction can be a key concern in some of these industries. For example, the automotive industry needs to reduce weight to minimize fuel consumption.

Traditionally, resistance spot welding is the leading connection technology for several industries' constructions. Due to technical issues, problems, cost, time, pollution, and other reasons, industries have begun to shift from traditional joining methods to mechanical joining methods such as clinching (often called mechanical interlock connection process). Contrary to welding, clinching is inflexible, but fast, fatigue resistant, accurate, and cheap when used in mass production [1].

The clinching joining method has become a popular alternative to conventional resistance spot welding due to the rising use of several materials, which are hard or impossible to be joined by welding. The clinching technique has been known from many years; the first patent of the clinching concept was in 1897 in Germany. Until the 1980s, the technology was not widely used in industry [2]. Only in recent years has interest in the use of clinching joining increased in industry, as clinching was successfully implemented to complement or even replace other joining techniques such as spot welding [3]. In the clinching process, two sheets of metal are joined using only a die and a punch. The clinching process consists of two principal actions, forming and drawing, that cause the creation of the interlock between the sheet's metal layers. During the process, the sheets are plastically deformed; the punch is moved with the required force depending on the thickness and the strength of the materials to be joined, whereas the die is fixed during the process. The size of the tools and friction coefficient are some of the major factors that influence the clinching joint [4].

Regrettably, this process is still early in its development despite rapid advances in recent years; it requires much more research to achieve the point where accuracy, high quality, and optimal strength of the joints become comparable to industry

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standard. In order to be adopted on a larger scale, some aspects of the process need to be further studied and clarified. It is impossible to achieve this goal without a complete understanding of the mechanics and relevant parameters. Therefore, this article critically summarizes the published efforts of recent years toward improving the knowledge of the clinching process by experimental tests where the loading conditions of a clinched joint can be static or dynamic whereas fatigue behavior, impact resistance, and vibration properties are linked with the latter.

2 Clinching process

2.1 The mechanics of joint formation

The clinching process simply includes a set of tools (punch and dies) by which clinched connections can be created. The principle of clinching is that metal parts are deformed locally and connected together without any additional materials such as glue or fastener. Clinching connection methods can be used on materials of various thicknesses; it can also be used for multiple materials, with different individual thicknesses, all at the same time. In addition, the clinching process requires a force that depends on the material properties and the size of the tool. One aspect that characterizes clinching in contrast with other connection methods is that there is no heat introduced into the joined specimens. Clinching is therefore considered to be a cheap and flexible process. Figure 1 illustrates the basic principle of the clinching process [5].

2.2 Comparison with other joining technologies

The clinching machines are simple to use and easily insertable in the production processes. In fact, for functioning, they need only compressed air at pressures between 2 and 7 bar. Different types of equipment exist, suitable for performing the work and can be used in both ways: static (workbench) or portable; moreover, they are easy to automate. The punching and forming process is described and illustrated in stages. In practice, clinching is performed at one stroke at a time. Tooling parts must be perfectly aligned and the workpiece is to be correctly presented to the tooling. For best results, the thicker or stronger sheet is always facing the punch.

The clinching joining technology has a primary aim, other than supplying an up-to-date and innovative joining technology, to reduce production costs. The cost saving can result from various factors:

- Low investment cost: no exhaust devices, no cooling, and no expensive electrical installations
- Low operating costs: low power consumption, no power consumption during idle time, low costs for wear parts due to long life of the tool, and no additional power consumption resulting from operation of exhausting devices
- No reworking costs: no damage to coating and no "burn-off" as with spot welding
- Short cycle times: short joining process and high automation level

Figure 2 shows the comparison of costs between clinching and some different joining processes and materials.

Furthermore, the clinching joining method is very promising since, compared to other joining methods, it is easier to use and has shorter pressing times and the parts to be joined are subjected to a lower heat stress, as shown in Table 1.

However, regarding the performance of the clinching process, there are different factors and areas to determine the strength of the joint; static strength, dynamic strength, and crash resistance (Table 2). Moreover, the strength values depend on some combined values such as the material (type and thickness), the joining direction (thin into thick, hard into soft), diameter of the clinching point, and geometry of the clinching point.

2.3 Classification of joining types

There are so many types of clinch that it is difficult to illustrate them all in this paper. Only the most predominant types will be classified and discussed here, such as cylinder, beam, star, flat, and self-piercing elements.

The two most important classification aspects are the composition of the joint and its related production method. Thus, all the joining process types can be classified or grouped into two general categories. The first group is clinch joining without the aid of another material (no filler material is added during joining). The round, square flat, and star joints are examples of clinching joints in this category. In addition, this category of clinching can be divided into two groups

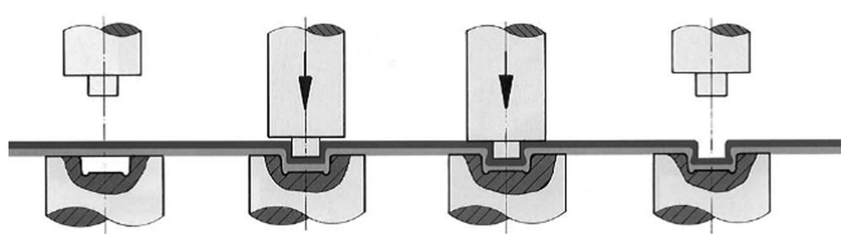


Fig. 1 The basic principle of the clinching process [5]

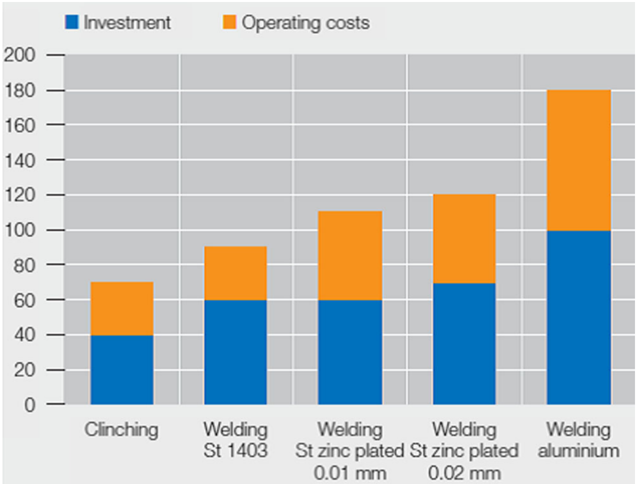


Fig. 2 Comparison of costs for different joining processes and materials [6]

depending on the process itself: shear clinching, such as beam and star, which includes only the sheets to be cut; and the second group is clinch joining with auxiliary material. Based on the structure of the elements, clinching can also be classified into two basic types: shear clinching (beam, star) and press clinching (cylinder, flat). Figure 3 shows the two principles of joining process with two types of tools, round and square.

In shear clinching, the two plates to be joined are cut and then connected together by interlocking. In the pressing clinching process, the punch pushes the surface of the upper sheet resulting in the sheets being connected locally by penetrating into the groove of the die without any cutting process and without any scrap material. In the case of self-piercing and self-riveting, the joint is created by the means of an additional or supportive material. In clinching, there is no need to drill the sheets before joining; as the auxiliary material is punched, it draws itself into the two sheets and completely penetrates both sheets of metal. In other words, the additional material is pressed and formed into the desired shape [9]. Figure 4 depicts a flow diagram identifying the different types of clinching processes.

While the joining mechanisms of mechanical joints rely on the same principles, the occurrence of the joints differs concerning their geometrical and mechanical characteristics. Table 3 gives an overview on the most common mechanical joining processes and classifies them with respect to their geometric appearance [10].

2.4 Factors influencing clinching forming

There are a number of factors affecting clinch forming, such as interlock between the two sheets, upper and lower sheet thinning, and the reduction in the bottom sheet's thickness. Different studies considered these factors as the major parameters of the process joinability. In addition, these factors are influenced by the tool's geometric parameters, like the shape of the punch and the die. Brani and Benzegaou [11] studied the influence of certain parameters such as the geometry of the tools, mechanical characteristics of material, and the friction on the clinch process. The mechanical or geometric parameters' influence on the results of the process was significant and their correct design will ensure the best formation of the clinch point and its mechanical resistance. Figure 5 shows the influence of friction, punch diameter, and die height on the effort of the punch.

Abe et al. [12] investigated the joinability of mild steel and high-strength steel sheets with aluminum alloy. The study found that the material's ductility was the most important factor that limited the mechanical clinching connection method. Another study by Abe et al. [13] to investigate the joinability of the hot dip coated steel sheets using the mechanical clinching process showed that the joining method can be used for joining galvanized plates. Moreover, they deduced that the punch corner radius, die groove, and the die depths are major factors affecting the connection of the two sheets and the layer thickness. Indeed, the increase of the punch corner radius caused a rise in the minimum layer thickness which is related to the small plastic deformation of the upper sheet. However, the large corner radius gave no interlock forming between the two sheets (Fig. 6). In addition, the die cavity was incomplete when eliminating the die groove creating the joint without interlock. Recently, another study has shown that the main parameters affecting the joining of high-strength steel with aluminum alloy sheets is the shape of the die, i.e., depth of the die, diameter of the die, and the die groove. In addition, the differences in the flow stresses between the two unequal strength sheets (Al and HSS) make the joint critical and difficult [14].

De Paula et al. [15] used the finite element method to determine the main parameters affecting the clinching joints. They found that the punch corners with groove depth and die shape are the influential geometric parameters that enhanced the interlock length of the clinched joint. Another

Table 1 Comparison of the technological characteristics of fastening methods [7]

Joining technology characteristic	Adhesive joining	Spot welding	Clinching	Riveting
Technology process parameters	Very complicated	Complicated	Limited	Limited
Time	Short to long	Very short	Very short	Short to long
Temperature	Relatively low	Very high	Very low	Very low
Pressure	Low to high	Relatively high	Relatively high	Relatively high

Table 2 Comparison of different joining technologies [6]

	Clinching	Self-pierce riveting	Riveting	Screwing	Spot welding	Adhesion
Corrosion on coated material	Low	Low	Low	Low	High	None
Changes in structure and strength at the joining location	None	None	None	None	Yes	None
Dynamic strength	Very good	Very good	Suboptimal	Suboptimal	Suboptimal	Good
Crash resistance	Suboptimal	Very good	Suboptimal	Suboptimal	Suboptimal	Good
Static strength:						
1. Shear tension	Good	Very good	Very good	Very good	Very good	Good
2. Pullout tension	Good	Very good	Very good	Very good	Very good	Good
Method in combination with adhesion	Optimal	Optimal	Possible	Possible	Poor	–
Edges–burrs–chips	None	None	None	Edges	None	None
Required fasteners	None	Self-pierce rivet	Rivet	Screws nuts washers thread	None	Adhesive
Additional process steps	None	Feeding	Feeding, caulking	Feeding, screwing	Coated surfaces	Pressing curing
Costs per joint	Very low	Low	Very high	Very high	High	High
Energy input	Low	Low	High	High	Very high	Very high
Economic efficiency	Very good	Good	Poor	Poor	Suboptimal	Suboptimal
Environmental friendliness at the workplace	Very good	Very good	Good	Good	Poor	Very poor
Handling	Very easy	Easy	Easy	Easy	Easy	Complex
Reproducibility	Very good	Very good	Good	Good	Satisfactory	Good
Dependence of resulting joint on surface condition	Low	None	None	Low	High	Very high
Pre-operation	None	None	Drilling	Drilling	Washing pickling	Washing pickling

study conducted by Jayasekara et al. [16] showed that the die diameter and depth were the main critical geometrical factors that influence the quality of the joints. Kim [17] conducted an experimental study to estimate the optimal punch force to obtain the highest clinched resistance value where a series of tensile tests were implemented on the sheet metal clinched joint assembled with different punch force. A parametric study for the joining of dissimilar material (aluminum with high-strength steel sheets) was performed by Lee et al. [18]. The outcome of the study showed that the most significant factor in the process is the die radius. Additionally, the strength of the joints was strongly influenced by the undercut length and the thickness of the upper sheet neck. The study also performed a relationship between die depth and interlock length associated with cracks in different locations in the joint. Furthermore, proportional relations between die radii and the neck thickness and an opposite relationship with the mechanical interlock length of the clinched joint were found. Mucha [19, 20] found that the die geometry, especially the die groove width, was the most important parameter affecting the material flow and the energy consumption of the mechanical joining method. In addition, the optimal die shape had a great effect on the interlock length of the joint causing a decrease of the force applied to the tools, which increased the lifetime of the clinching machine. A basic model of clinching with magnesium alloy was established by Han et al. [21]. The joint interlock, neck thickness, bottom thickness, bottom die, die depth, groove depth, groove fillet radius, groove width, and draft angle were found to be the main geometrical parameters of the clinched joints. The results offered a better insight into the practical application of clinching to enhance the joint strength.

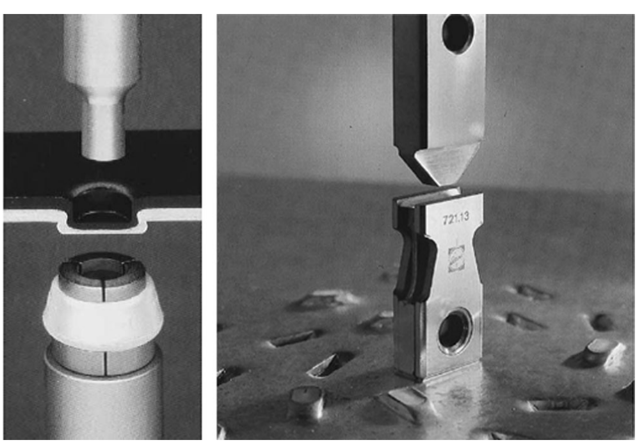


Fig. 3 Two types of clinching tools: a round joint (*left*) and a square (*right*) [8]

2.5 Joint failure mechanics

The failure in clinching joining occurs under different modes. The first mode happens when the joint opens with

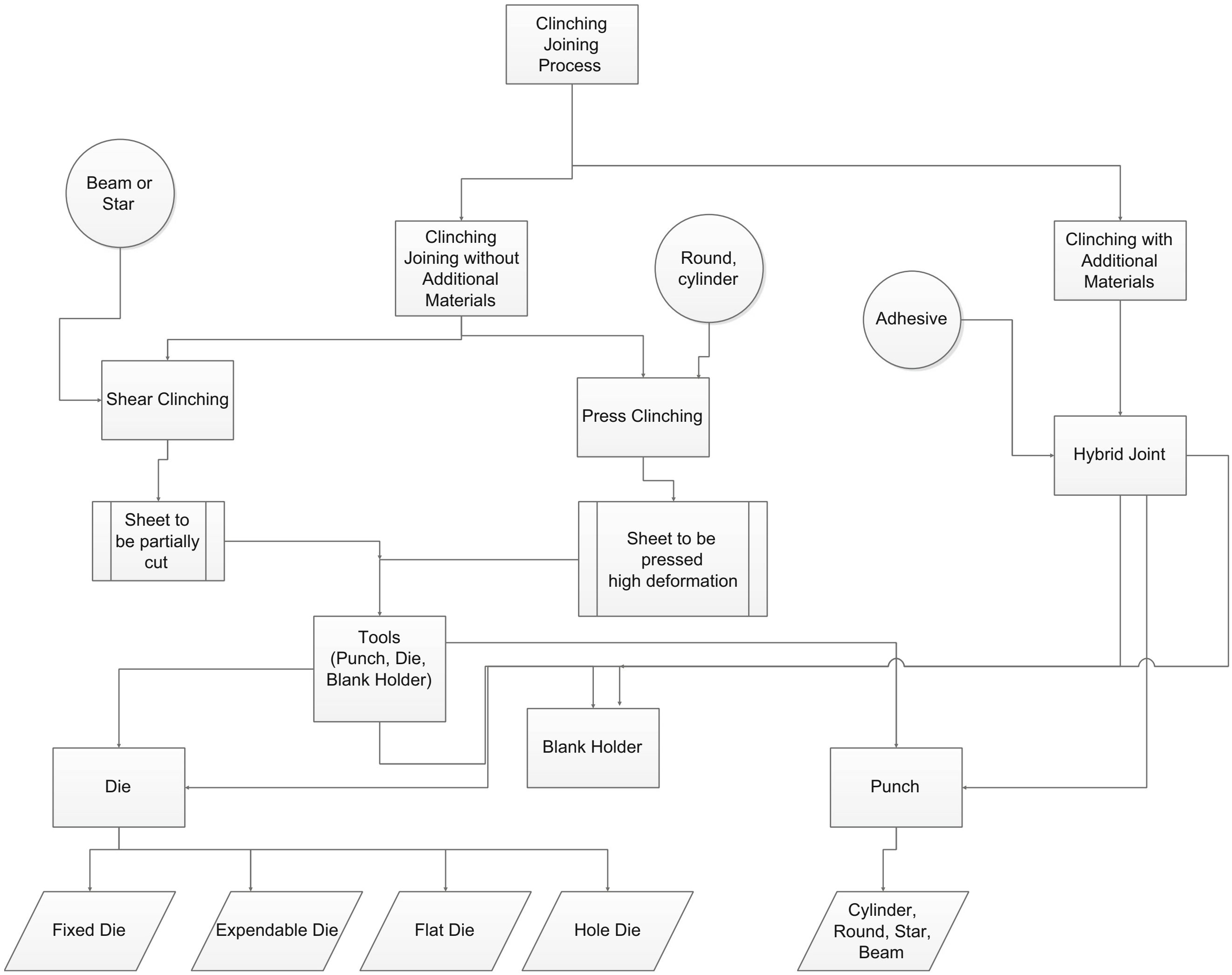


Fig. 4 Different types of clinching processes

respect to the concentrated deformation of the sheets. This is normally due to the lack of the interlocking between the two sheets. The second mode is caused by the large thinning of the material in the neck area of the upper sheet leading to fracture in that location. This is due to the low ductility of the material. The third mode is a combination of the previous two modes. Lastly, the crack's occurrence in the bottom of the joints is due to the generated tensile stress that can be prevented by eliminating the groove depth [14, 22].

The plate thickness configuration is one of the main parameters affecting the forming and the strength of the clinched joint. In addition, fracture in the neck area, and the partial material separation of the two sheets or the complete one are due to insufficient material displacement in the groove of the die and the small mechanical interlock lengths. On the other hand, the maximum shear force magnitude was strongly influenced by various material thickness arrangements related to the proper die groove size [23].

An analytical formulation was conducted by Lee et al. [24] using the typical failure mode (neck fracture, bottom separation) of the round clinching joint. Generally, neck thinning until fracture occurred when stress (load) reached the ultimate tensile stress of the upper sheet, causing a fracture in the neck area. In addition, segregation between the two sheets occurred in the bottom area of the joint due to the small mechanical interlock length. To validate the results of the analytical model, experiments were conducted with different joint configurations, whereas the results show good agreements between analytical solution and experiments. In another study dealing with joining of aluminum alloy and high tensile steel sheets, cracks appeared in the joint due to the difference of the stress flow of the two sheets and the difference in ductility of the two materials [19].

Zhao et al. [25] conducted an experimental and numerical study to evaluate the failure mode of clinched joints. They classified the failure mode into two categories: the normal and the unusual failure mode. The normal failure mode was

Table 3 Frequently used mechanical joining techniques arranged by their dimensional geometry [10]

Process	Closed Profiles/ Axisymmetric	Open Profiles/ Planar
Clinching	In general not utilized	Primarily utilized
Riveting	In general not utilized	Primarily utilized
Hemming	Primarily utilized	Primarily utilized
Hydroforming	Primarily utilized	In general not utilized
Rolling	Primarily utilized	In general not utilized
Extrusion	Primarily utilized	In general not utilized
EMPT	Primarily utilized	In general not utilized

Legend
In general not utilized
Primarily utilized

determined by the tensile and shear test used for evaluating both the strength and the quality of the clinched joint. In addition, the tension load is vertical and the shear force is horizontal to the fracture direction. Furthermore, the quality of the joint was evaluated by comparing the neck thickness and the mechanical interlock length between the two plates after joining. The results revealed that when the neck thickness had the same value as the interlock length, the joint will directly fail when the two sheets were subjected to a small load value. However, for a value of the interlock length that is lower than the neck thickness, it was found that the tensile strength has a lower value than the shear strength. On the other hand, the unusual failure model was determined by the short length of the mechanical interlock and the thin neck thickness. Generally, fracture occurs in the neck thickness; a thin neck will cause the upper sheet in the neck to fracture, and small undercut will lead to the separation of the upper sheet and the lower sheet because of the weaker interlock between the two. Figure 7 presents the failures and the load–stroke curves for the tension test of three different joining methods.

3 Mechanical properties

Generally, in mechanical joining, there are two loading cases: static (rigid body with equilibrium) or dynamic (cyclic loads). In addition, there are two trends for examination of the joints: experimentally, with loading of the joints and measuring the mechanical response, and by calculation of the mechanical behavior with the selection of accurate methods.

Varis [8] evaluated the suitability of clinching methods for joining high tensile construction steel metal using square and round shape joining tools. Only the shear strength of the joints was tested in the experiment. Figure 8 illustrates the differences between various tool shapes related to the shear load of the joint.

The results demonstrated large differences between round and square joints when maximum sizes are used. This led to the hypothesis that comparisons are not accurate for such kinds of joints. Furthermore, the results cannot be used for a precise comparison of clinching with joining methods such as screwing and riveting or spot welding.

3.1 Static behavior

To approximate the ultimate tensile strength with the static behavior of the clinched joints, tensile tests were used for two dissimilar conjunction configurations (longitudinal and transverse configuration). The results obtained from Carboni et al. [26] showed that the final strength of the clinched joint is independent of the direction of the clinch connection. Coppieters et al. [27] investigated the hardening behavior of the mild deep drawing steel sheets (DC05) by minimizing the differences between the internal and external work in the necking area within the tensile test and using a digital image correlation technique. In addition, an analytical approach was used for measuring the pullout strength or axial strength of joining mild deep drawing steel (DC05) using mechanical joining such as the clinching technique. Moreover, this study introduced a new experimental setup used for testing the clinched joints of the two sheets, which is called "box test." These new experiments were used to estimate the pullout resistance when finite element code is not available to determine the final geometry and the material behavior after forming. The results of the study showed that the frictional state between the two similar mild steel sheets used in the study, and the material properties at large plastic strain exhibited a complicated behavior that was strongly affecting the accuracy of

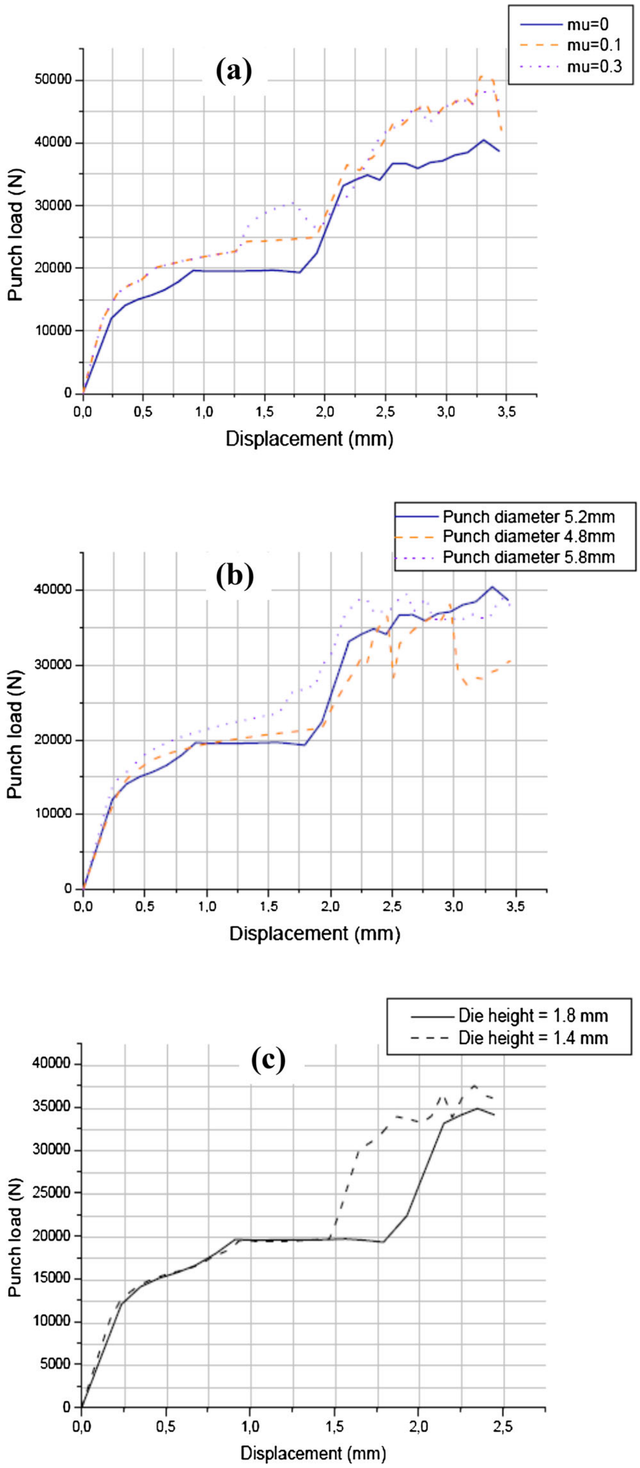


Fig. 5 Load-displacement curves for various: **a** friction coefficients, **b** punch diameters, and **c** die heights [11]

the analytical approach. However, new research can be conducted to investigate the pullout strength of clinched joints of dissimilar materials.

The mechanical properties and behavior of DC05 clinched joints were studied by Coppieters et al. [28] using multi-purpose testing tools. A multi-axial loading device was

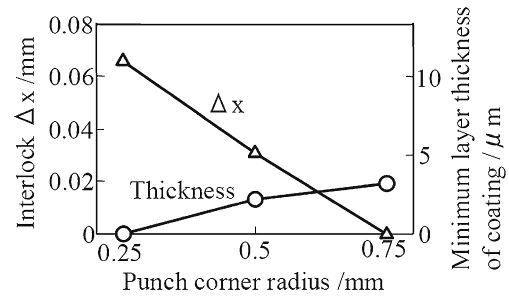


Fig. 6 Effect of punch radius on interlock and layer thickness of top surface obtained from experiment [13]

developed to measure the shear and tensile ratio in fabricated two-metal-sheet clinched joints. The investigation results pointed out that the strength of the joints increased when shear values increased. In addition, a finite element model was used to reproduce the experimental results. However, it was difficult to identify the post-necking hardening characteristics of the sheet metal which needs further investigation into how to be carried out. Furthermore, friction components of the clinching process are one of the important factors affecting the joints, and because there is no available friction examination for the metal sheet, friction was considered by correlating values using numerical approaches. The plastic material behavior was investigated through the extrapolation of the pre-necking hardening behavior (EM), the multi-layered upsetting test (MLUT), and the post-necking tensile experiment (PNTE). Figure 9 shows the results obtained for DC05, and it can be inferred that the flow stress under biaxial tension is larger than under uniaxial conditions. Two commonly used hardening laws are identified, namely, the Swift ($\sigma_{eq}=K(\epsilon_0+\epsilon_{eq}^{pl})^n$) and the Voce $\sigma_{eq} = C\left(1-me^{-k\epsilon_{eq}^{pl}}\right)$. For each identified

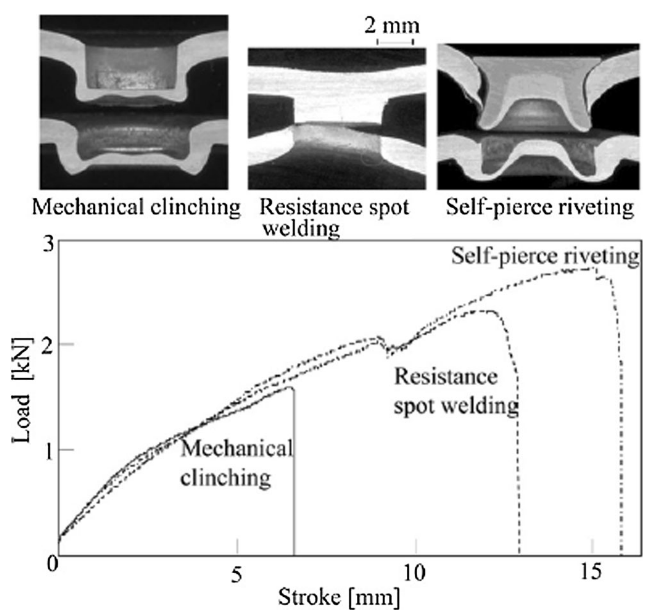


Fig. 7 Load per stroke curve for three different joining methods [25]

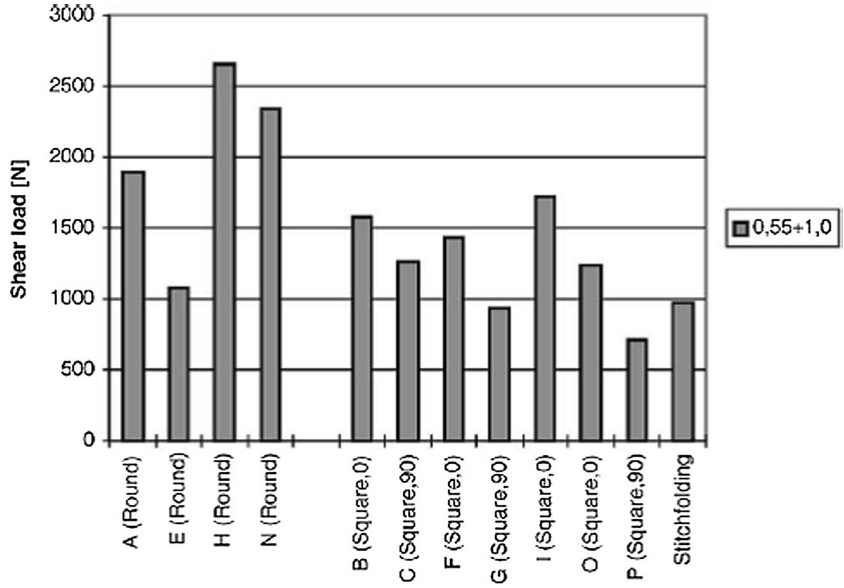


Fig. 8 Shear load for square and round shape clinching tools [8]

flow curve shown in Fig. 9, the frictional conditions (μ_i and μ_t are the inter-sheet friction and the friction between the tools and the sheets, respectively) during clinch forming were identified. These data sets are accompanied with friction values during clinch forming: EM-Swift (μ_t=0.167), MLUT-Swift (μ_t=0.126), MLUT-Voce (μ_t=0.198), and PNTE-Swift (μ_t= 0.137). The authors also explained that there are still many difficulties preventing the reproduction of experiments.

Gibmeier et al. [29] measured the residual stresses in the clinched joint using X-ray and Neutron diffraction methods. They also studied the effect of the residual stress on the mechanical behavior for two dissimilar materials and two different clinching techniques (Eckold & TOX tools). The largest values of plastic deformation occurred in the clinching undercut area. The study showed that there is compressive residual stress distributed inside the clinch and around the joint. However, compressive residual stress was balanced by tensile residual stresses. Moreover, the residual stress extended to about 4.0 mm outside the clinched diameter when using the Eckold tools while it was around 6.0 mm outside the clinched joint when using the TOX clinched tool.

He et al. [30] investigated the energy absorption and the strength of both standard and hybrid clinched connection for aluminum sheet metal alloy 7075. They used the tensile-shear failure test to estimate the ultimate magnitude of the clinched connection strength. In addition, the study showed that the maximum load and energy absorption of the standard clinched joint are lower than those of the hybrid clinched joint as illustrated in Fig. 10.

Additionally, the main failure mode in the two types of joints was neck failure. Jayasekara et al. [16] examined the separation strength with the configuration of peel and tensile-shear tests of the clinched joint of aluminum alloy 5754. The quality of the joints was estimated by examining the thickness of the neck, measuring the mechanical interlock length of the joint, and estimating the bottom thickness of the clinched

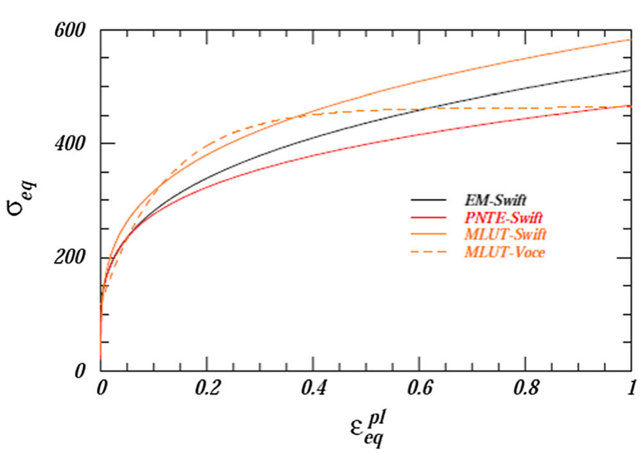


Fig. 9 Identified flow curves for DC05 [28]

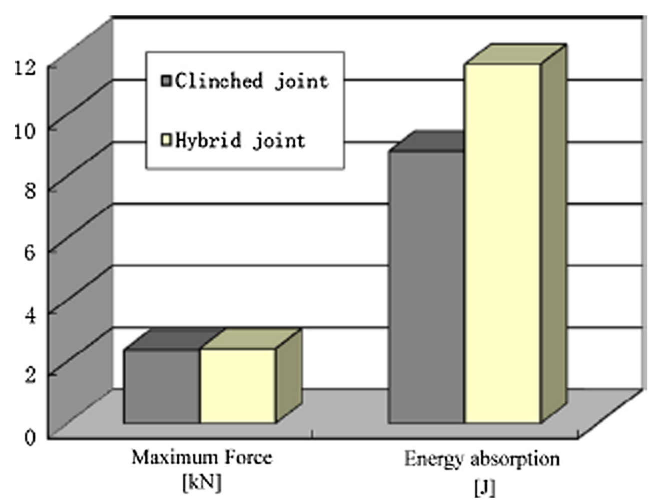


Fig. 10 Intercepts of strength and the energy absorption for clinched joints and clinch-bonded hybrid joints [30]

connection. These factors were used for evaluating the separation failure mode.

Jomaa et al. [31] conducted an analysis on the strength to pull out the mechanical interlock connection of thin sheet metal fabrication. The results illustrated that the thinning of the bottom sheets was one of the most important parameters regarding the joinability of the clinching methods. Moreover, high quality, and accepted strength of the clinched joint were affected strongly by the interlock length which is very difficult to be measured accurately. Generally, the joinability can be measured by conducting pure tension tests, shear tests, and pullout tests. These tests were used in the study to determine the resistance of the clinched joint as well as spot welding and riveted connections. In addition, different test specimen configurations were used such as cross section and pure shear test configuration.

The carrying capacity of the mechanical joining clinching methods was investigated with different arrangements of material grade [23]. High-strength steel sheets, advanced strength metal plate, and drawn steel were connected and tested by the standard inspection procedure of spot resistance welding testing. Different material arrangements and configurations were tested. Figure 11 presents the maximum force, which destroys the spot weld and clinching joints for joined sheets of DD14 and DX53D+Z. Relatively good results have been achieved by increasing the clinching joints from one to two, but such joints still feature lower strength than spot weld joints. However, the orientation of the effective tools, punch, die, and joint diameter, strongly affected the clinched joints' strength. An experimental research by Nong et al. [32] provided basic information about the basic principle of formulating the press joining technology parameters. It was found that the strength of the spot welding joints is higher than the impact resistance of the press joining methods. Another study by Dost et al. [33] showed that the resistance spot welding is better in strength than the clinching joining methods, especially when the sheet metal thickness is increased.

In order to study and estimate the properties and characteristics of the sheet metal connection by different mechanical joining processes such as clinching and self-piercing riveting

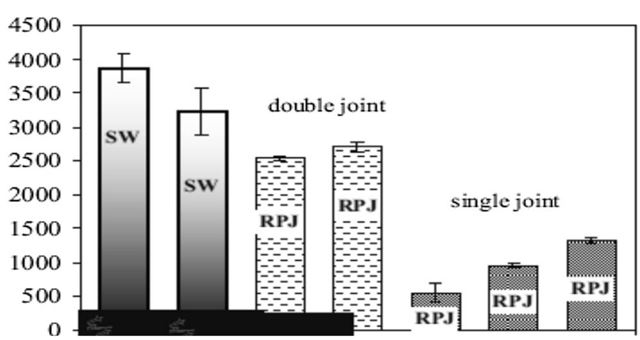


Fig. 11 The comparison of maximum shearing force for various joint arrangements (*SW*, spot welding; *RPJ*, clinch round press joints) [23]

technique, tensile, metallography, and micro-hardness tests were employed to calculate the carrying capacity of the joints and to determine the micro-hardness of the critical area after the forming process. The tested materials were selected based on the sheet metals utilized in the automotive industry, i.e., micro-alloyed steel H220DP (0.8 mm), extra deep drawing steel DC06 (0.7 mm), and mild steel (0.9 mm). The results showed that the clinching process has a resistance value than the self-piercing riveting process. However, the metallographic analysis at different load capacities indicated that there were no cracks in the clinched point after forming [34]. Lambiase et al. [35] conducted a study to evaluate the material flow of the extendable die clinched joint using different tests. One of these tests was the standard tensile-shear test. Varying forming loads were used in fabricating the test specimen. The results showed that the forming forces strongly affected the joints' strength as well as the undercut and the neck thicknesses. Furthermore, the flow of the material before the extendable die started to open exhibited the same behavior as of the closed or fixed die. However, the flow of the material is different in the last stage when the die started moving and created larger volume space.

An analytical optimization approach was carried out by Lee et al. [24] to design the clinching tools. The optimization procedure depended on an analytical approach for predicting the pullout strength. In addition, the authors considered the analytical model for joint strength for two failure modes: neck fracture and button separation mode (insufficient geometrical interlocking). The strength and the crash resistance of the clinched joint were evaluated using H-type tensile tests and impact tests. The impact test showed that the crash resistance for both self-piercing riveting and clinching was almost the same. On the other hand, the strength of the clinched joint was lower than the resistance of the self-piercing.

Lately, a numerical and experimental research about the use of clinching for joining thick sheets was performed by Mauermann et al. [1]. The outcome of the pullout and shear load test experiments showed that the upper sheet thickness must be higher than the lower plate in order to obtain the optimal strength value of the clinched joint. In addition, it was found that the separation between the upper and the bottom sheet is due to the pullout force caused by the small length of the mechanical interlock or as a result of the large strength ratio of the two sheets. However, the neck failure in the clinched joint was dramatically affected by the loading type and the shear force and caused a fracture in the thinning area of the upper sheet in almost all cases. The major restriction in clinching thick sheets is the high value of the load needed to obtain and create the joint.

Mori et al. [36] performed a study about joining materials by large plastic deformation. Different metallurgical and mechanical joining techniques were investigated. The data obtained from the study illustrated that there were two modes of joint failure: large thinning of the upper sheet causing a neck fracture and the separation of the two bottom sheets due to the mechanical interlock length of the clinched joint.

In addition, it was shown in various studies that the clinching method was useful and suitable for joining distinct material properties such as coated and un-coated metal sheets, aluminum, magnesium, mild steel, and high-strength metal sheets [9]. In general, the strength of round clinching joints was found to be higher compared to the that of the square one [37]. The corrosion resistance for the round sheets was investigated by two different studies and the results showed that to minimize or prevent the rust occurrence, a flat bottom clinched joint needs to be developed [14, 15]. Heat was introduced for the clinched joint when joining materials with low ductility such as the connection of magnesium material sheets. The results showed that the heating time varies with the die shape and that less heating time is needed with the dieless clinching process [38, 39]

An experimental study was conducted to inspect the quality of the clinching joint of high-strength thin steel H320LA visually, and by examining the strength of the connection of the two sheets [20, 21]. To ensure the integrity and the quality of the clinched point, the bottom thickness of the two sheets after forming the joint was measured. More recently, Mucha et al. [40] investigated shear strength for several techniques with different joint combinations (single/double joint; different load direction, etc.). The results of the study showed that the completed double and different combination joints in the experiments are efficient as shown in Fig. 12. The clinching joints are the cheapest ones from the manufacturing point of view, and thus the most competitive. In addition, the data obtained from the experiments indicated that when forces are parallel to the direction of both round and rectangular clinch joints, the shear resistance of the clinched joint is higher than when the load is perpendicular.

Recently, the static strength and energy absorption of the clinched joint were evaluated by Liu et al. [41] by examining three different aluminum alloys (7075, 5052, Y2). The results of the study showed that when the higher strength alloy was located in the die side, the resistance of the mechanical connections increased. On the other hand, there was no relation between the energy consumption and the strength of the material.

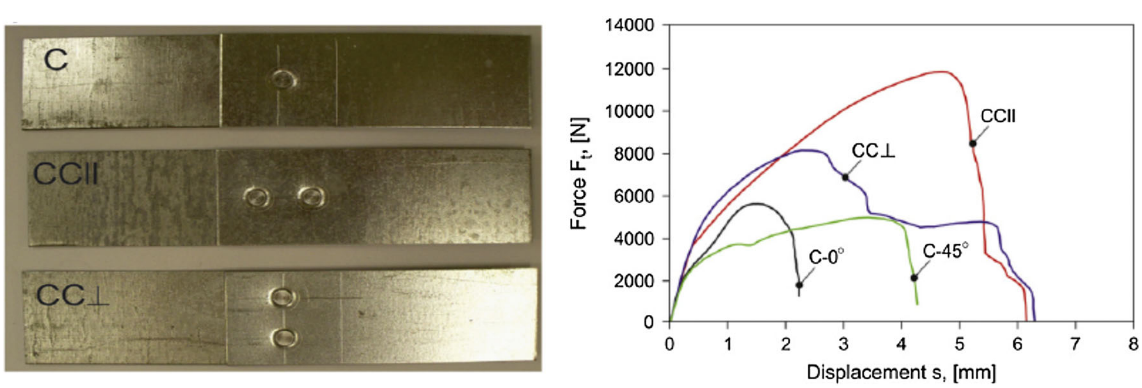
Kai et al. [42] introduced an inspection procedure to detect cracks generated after forming the clinched point. It was based on the acquisition of a series of images for the two sheets connected mechanically and subjected to shear load. The research outcome showed the capability of the method for detecting the cracks in the clinched joint.

3.2 Fatigue behavior of clinching joints

There is a limited scientific research regarding the fatigue behavior of the clinching joints. Carboni et al. [26] studied the static and fatigue behavior of tensile-shear loaded joints obtained by clinching. Two different specimen arrangements were used, longitudinal and transversal clinched joints, in order to investigate the effect of changing the load direction on the resistance of the joint. In addition, fatigue tests were conducted using different stress ratios. The results showed that the different configurations of the joint did not have an important effect on the fatigue behavior of the joint as depicted in Fig. 13. Moreover, when comparing the values of the fatigue limit with stress ratios 0.1 and 0.3, there were similarities between the values obtained which were around 50 % of the ultimate stress. This is higher than the value obtained by spot welding.

A similar study conducted by Kim [17] showed good agreement with Carboni et al. [26] as seen from Fig. 14. The fatigue endurance limit (R=0.1, 5–20-Hz cyclic load) of the clinched joint of cold-rolled steel was around 43 % of the maximum tensile force.

Another study for clinch joining fatigue behavior was conducted by Mauermann et al. [1], using the same load ratio (R=0.1 with 15–20-Hz frequency), with thick sheet



(a) (b)

Fig. 12 The examples of clinchrivet joint alignment (**a**) and their shearing curves (**b**) [40]

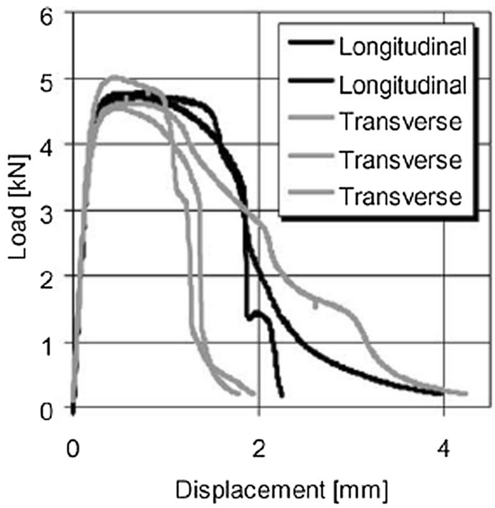


Fig. 13 Load per displacement curve for longitudinal and transverse arrangement of the clinch point [26]

metal. A comparison between different joining of metal sheet methods regarding the shear load force ratio was made. The outcome showed that clinching has an advantage over other methods (self-piercing riveting and spot welding) regarding the fatigue characteristics for both thick and thin sheet metals. One example is shown as showcased in Fig. 15. High cycle fatigue (HCF) is on comparable high level with thin sheet clinching. The ratio of shear load force HCF/static maximum load was 26.4:42.3. Under cyclic load, the level was 62 % from static strength level in this special case. The range of this ratio was usually between 50 and 80 % depending on the crack characteristic.

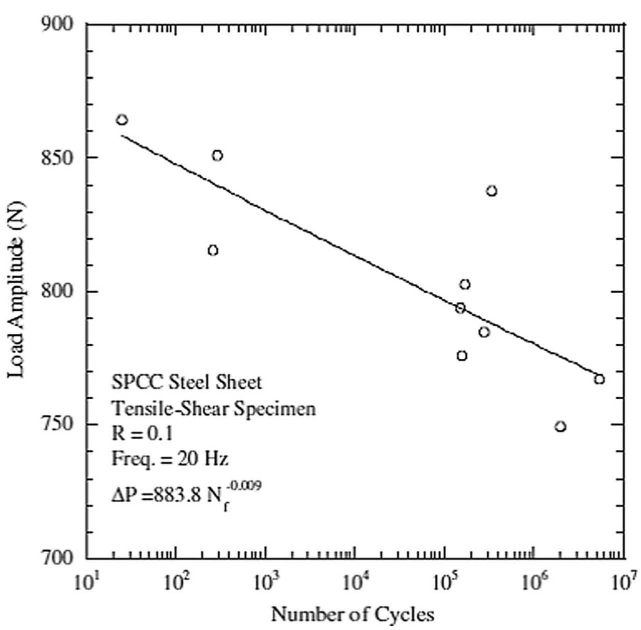


Fig. 14 Load amplitude against the number of cycles for a tensile-shear specimen [17]

4 Recent development of clinching joining technologies

Jurkanin [43] developed a new clinching technique called the TTOX-TWIN Point method of mechanical joining. This method can be used for joining materials of different thickness, and for various mechanical behaviors such as ferrous and non-ferrous metals. The researcher used an eccentric press machine with a shearing tool principle. The twin point method introduced a new concept for solving the rotation problem in the conventional clinched joint. The arrangement of the punch and the die is very significant for the purpose of avoiding failure or cracks in the joints during the connection process (Fig. 16).

Neugebauer et al. [39] presented the state of development and the application of the dieless mechanical joining process. The authors showed the advantages and practical examples of different process alternatives of the dieless and flat mechanical joining over the conventional joining process. The key difference between the two processes was the complete avoidance of an anvil side protrusion in flat clinch connections. The biggest advantage of the dieless joining method is the possibility of introducing heat to the sheets, or parts, by thermal conduction which cannot be achieved with other mechanical joining technologies that use a die as counter tool. At room temperature, magnesium has very restricted deformation properties. Furthermore, magnesium alloys cannot be joined by conventional clinching joining technology. At the beginning, this limitation was solved by conducting another clinching method such as a rectangular one. On the other hand, the benefit of using a non-cutting, single stroke clinching joining technique was more efficient. Hahn et al. [21] and Neugebauer et al. [38] introduced heat for increasing the formability of magnesium by pre-heating before joining. A counter tool with heated anvil was then used for joining the magnesium sheets; this process can also be called a dieless clinching method. The results showed that the punch corner radius was a very important factor for the dieless clinching process. Furthermore, redesigning the radius to be very large will cause a decrease in the dimension of the joint connection interlock. Another significant parameter related to the punch is the punch diameter; the larger the punch, the thicker the obtained neck. Moreover, the counter tool clinching method allows magnesium to be joined in shorter time due to the fast pre-heating of the sheets, and that will be an advantage over traditional clinching joining methods with a round die. However, it was discovered that good connection could be achieved with experimental results by matching the magnesium alloy response during compression tests with stacked round blanks [38].

Recently, a new development in clinching joining technology was proposed [44]. Conventional clinching technology cannot be used for visual rejoins or functional surfaces (e.g., sliding surfaces) because of the prominence of the joints. This

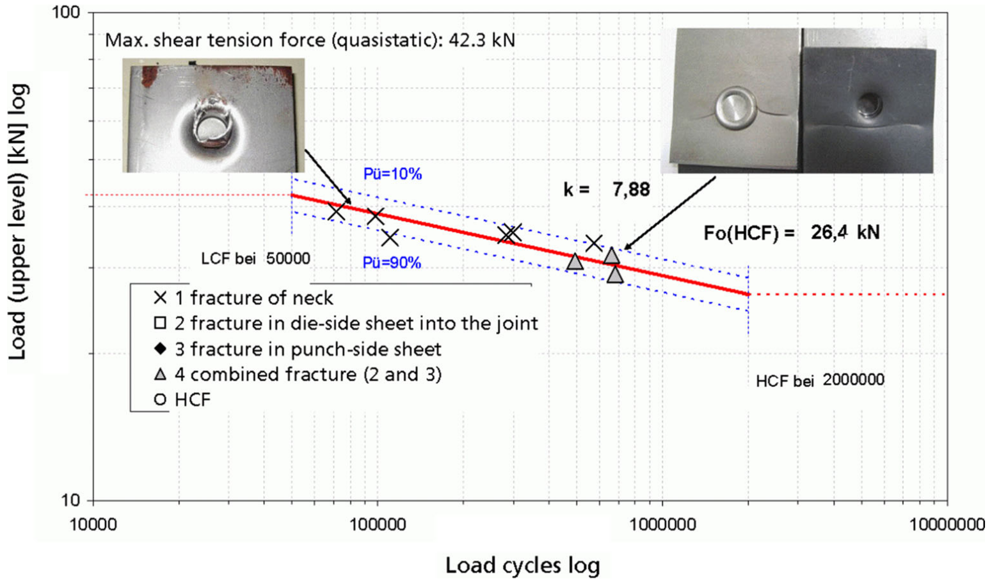


Fig. 15 Joint strength and typical fatigue curve [1]

prominence leads to develop a new technology called the flat clinching joint methods where the die in the conventional clinching methods is substituted by a planar anvil as illustrated in Fig. 17. The new design gave the opportunity to create a robust force and establish a suitable connection that could be used in visible areas. This method was utilized for joining different materials, such as metal composites, plastic and metal components (composite), cardboard, and corrugated board. The authors determined the connection properties by mechanical testing methods as well as cross tension and tensile-shear tests. The study showed that tensile-shear force and cross tension force for flat clinching were higher than in traditional clinched joints. Authors also introduced adhesive and sealant to the flat clinched joint; this type of joint can be used in heating and ventilation industries. In addition, it was found that the curing of the adhesive was very important in order to obtain the required strength of the joints. This new technology needs more investigation and more studies especially on the numerical simulation of the adhesives, and the modification of the tool geometries [44].

In general, there is very little knowledge to be found on hybrid clinching technology. Balawender et al. [45, 46] have performed an experimental survey of clinch-adhesive joints. The hybrid joint (the combination of two different joining processes "clinching and adhesive") for multi-materials (dissimilar materials) is a modern and innovative technology allowing the joining of different material densities with appropriate strength. This improvement aims to establish a durable and reliable light weight construction. Its practical implementation in the industrial and research fields is still limited and needs more investigation and research, especially to investigate the strength of the traditional and hybrid joint strengths, characteristics, and properties. The overlap hybrid joint was studied numerically and experimentally and the results indicated that the clinched joint before adhesive curing was stronger [46, 45]. In addition, hybrid clinched joints have some advantage regarding vibration and free torsion, and it is significantly influenced by the Young's modulus of the adhesive [47].

Recently, Wen et al. [48] dealt with reshaping conventional clinching joints to decrease the clinched bulge as shown in Fig. 18. The material used to model the clinching process was

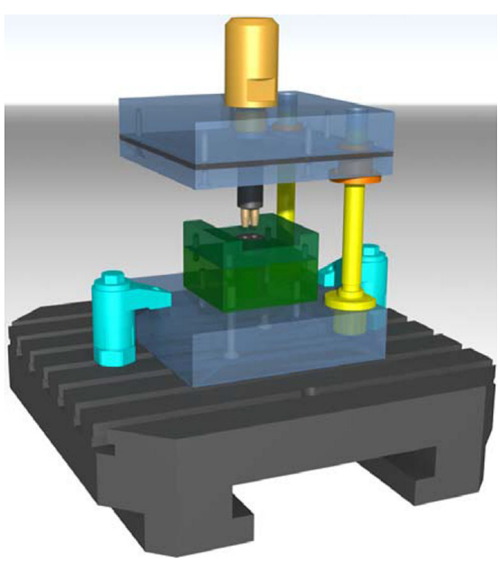


Fig. 16 The designed tool for TOX-TWIN Point joining method [43]

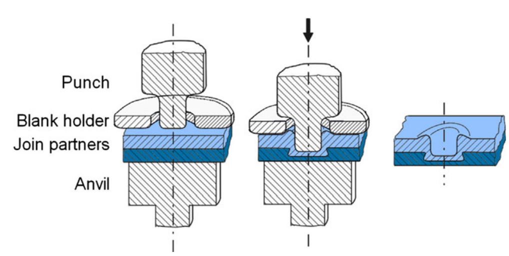


Fig. 17 Schematic drawings for the flat clinching principle [44]

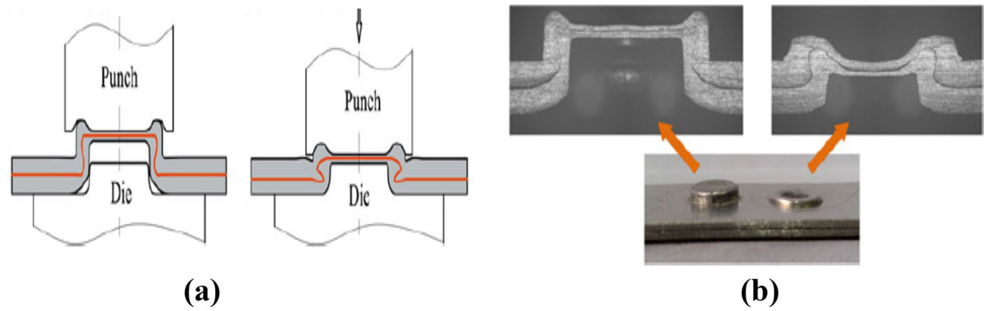


Fig. 18 **a** Conventional clinching joint (*right*) and clinching joint after reshaping (*left*). **b** Final view of the clinching joints before and after reshaping [48]

Aluminum alloy 6063 with a thickness of 0.8 mm. The mechanical properties of the AL 6063 alloy were obtained from a different study by Lee et al. [24]. In order to investigate the strength of the clinching joints before and after the process modifications, an optimization tool and orthogonal design were introduced to determine the geometry of the reshaping tool parameters. The experimental and simulation results obtained gave clear indication that the reshaping technique is feasible. Meanwhile, the pullout strength of the joint was enhanced by reducing the protrusion height of the clinch joints. Reshaping the tool geometry played a major role in the strength of the reshaped clinching joints [48].

Lee et al. [49, 50] developed a new mechanical joining method called "hole clinching" for connecting dissimilar materials. It was used as a modern technological method for joining different materials in the automotive industry. In this process, the material is drawn into a die cavity and flown inside the hole in the lower sheet creating the mechanical interlock as illustrated in Fig. 19. It was found that the sheets' arrangement is very important. Indeed, the ductile material must be located at the punch position.

5 Finite element simulation of the clinching process

Finite element method (numerical method) originated from the need to solve complicated and sophisticated structural analysis problems in different engineering and non-engineering fields. Since the clinching joining process is considered a complex cold metalworking process, it obviously needs complete accurate information and knowledge of different parameters, such as the materials and friction behavior, in order to obtain a sufficiently precise finite element analysis (FEA) simulation. In addition, different commercial software was used for simulating the various clinching processes such as LS-DYNA, ANSYS, ABAQUS, DEFORM^{TM}-2D, ADINA, and MARC.

He [51] reviewed the main development in finite element analysis of clinched joints. Recently, using LS-DYNA FEA code, a computational model (2D axisymmetric model) was established by He et al. [30], as depicted in Fig. 20. The finite element method was used in order to simulate the clinching process formulation, and the tensile-shear failure tests of the clinched joint to investigate, evaluate, and determine the strength and energy associated with the joint.

Due to the large deformation associated with the clinching joint and the plastic deformation behavior of the material during the clinching simulation, some elements may become severely distorted. Consequently, the severely deformed meshes may cause numerical problems that can lead to inaccurate results. To alleviate this, the kill elements technique is used, which eliminates and dismantles the damaged elements in order to reduce the effects and the numerical problems caused by these elements. In addition, an implicit technique with Lagrange's formulation and a *r*-self adaptive approach was used. The friction coefficient was considered one of the strongly influential parameters affecting the quality of the joint. Because of the lack of the experimental data available, it is assumed to depend on the Coulomb friction coefficient law. Figure 21 illustrates the 2D numerical results along with the experimental ones, and a good agreement between them is noticed.

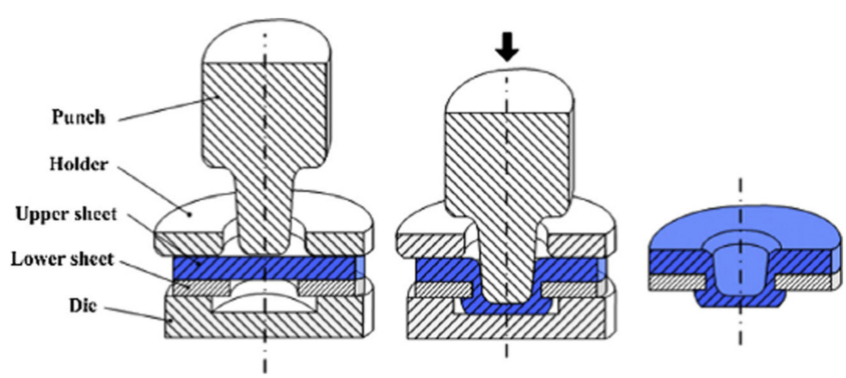
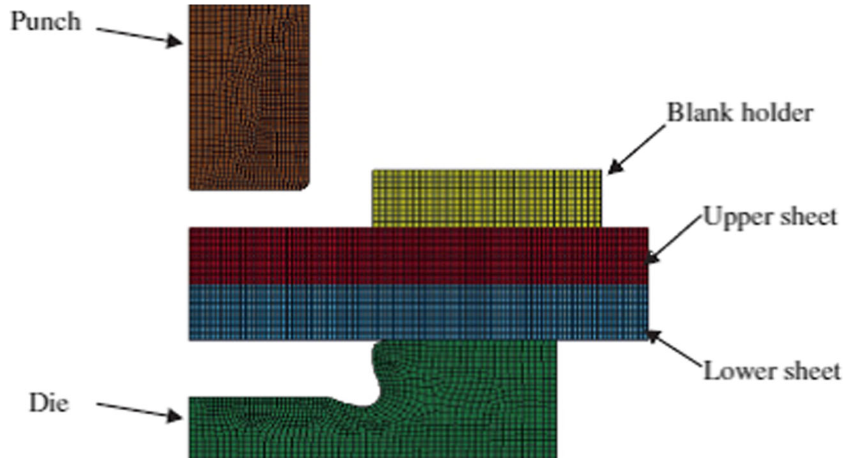


Fig. 19 Illustration of the Hole clinching technology [49]

Fig. 20 Two-dimensional axisymmetric model using LS-DYNA software showing the main components of the clinching process [30]



Moreover, a 3D model was used to simulate the tensile-shear test using ANSYS commercial software whereas the button separation and neck fracture failure mode were investigated. The outcome of the 3D simulation of both tests showed that the traditional clinching and the mixed joint had the same neck failure mode.

Recently, on one hand, an extensive comparison of the material flow pattern between the conventional clinched tool (fixed die) and the extensible one was carried out [35]. On the other hand, as depicted in Fig. 22, the extensible die groove was investigated in more details including the influence of the process parameters [35]

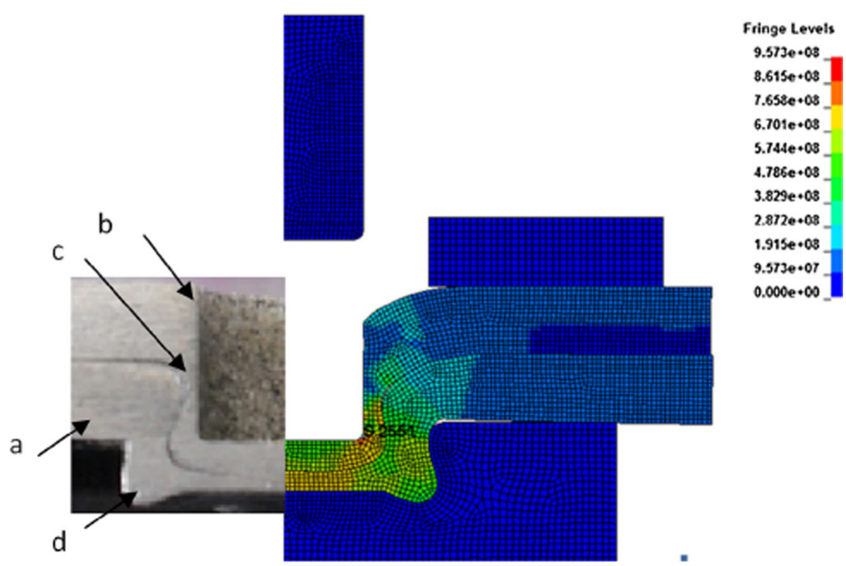
Lambiase et al. [53] investigated the joining of aluminum sheets using the extendable die technique and the power of the FE simulation and introduced the heat to the joint in order to increase the ductility of the sheets to obtain a high-quality joint free of defects.

Moreover, in order to give more detail about the simulation of the clinching process, an independent review is needed as a part of future work.

6 Summary

In this literature review on clinching, the mechanical behavior of a clinched joint and the recent developments in clinching technology are reviewed. It is noted that the available literature in this field is limited. There are a few papers regarding the material conditions and geometry of the joints. There is no clear methodical way for comparing numerical and experimental results in the available literature. Static responses of the clinched joints were investigated in experimental setups. However, there is little research regarding the numerical reproduction of these tests. There is also very little work concerning the dynamic resistance, impact behavior, and vibration properties of clinched joints. Furthermore, the researchers agreed that clinched connections have advantages over comparable spot welding regarding fatigue characteristics, but failure mechanisms, response, and behavior need more detail and knowledge to achieve a full understanding of these properties.

Fig. 21 Numerical and experimental results of a clinched joint [30]



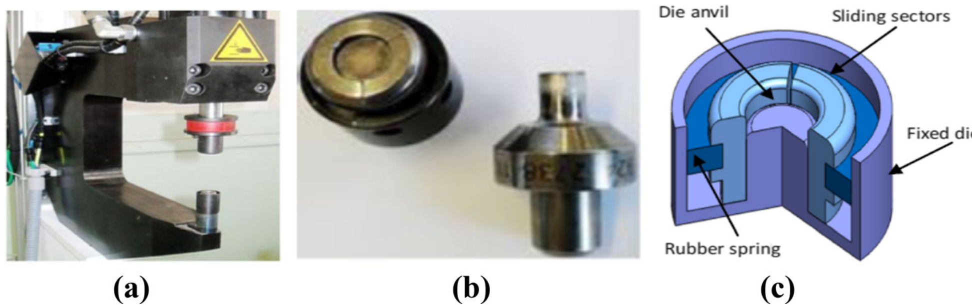


Fig. 22 Extendable clinching machine with tool configuration. **a** Clinching machine, **b** extendable die and punch tool, and **c** schematic drawing of the extendable die [52]

It is noted that, regardless of the limited amount of scientific research on the modeling of the clinching process and formability, there have been new clinching technologies developed in recent years. There appears to be a big gap between scientific studies, research, and the industrial application of this process.

7 Future trend

7.1 Forming process

The large plastic strain associated with the clinching forming process and the short contact length with high contact pressure under these conditions and the unavailability of friction tests for thin metal sheets is still a wide open research area for future work to obtain an accurate clinching forming process.

In addition, spring back effect on the clinched connection strength and final geometry is not very clear from the previous studies due to the small clinched area. However, this research area needs more investigation through experiments and numerical work to evaluate the spring back and its influence on the clinched connection process.

Moreover, the literature indicates that the auxiliary tool's effect on the mechanical joint is not examined in detail whereas it is an interesting area to be studied for future development of new clinching processes. Furthermore, there is still a need to investigate the optimal dimensions of the tools and joints. Indeed, the optimized geometry of the punch and the die will help to obtain high-strength and high-quality clinched joint that can be used in different applications and different locations in the industrial field. Furthermore, the arrangement of the clinching joints and its effect need to be better characterized in a standard way in order to help manufacturers and industries to have an easy access to this information for better use and application. These can be examined in future work using the finite element method.

7.2 Quality of the joint

There are different procedures and tests to determine the quality of the clinching joints: destructive and non-destructive techniques. Generally, the well-known inspection methods that are used to examine the quality of the clinched joints are to conduct tensile and shear strength tests on specimens after forming the joints which will eventually damage the latter. On the other hand, there are some non-destructive methods to measure the thickness of the bottom of the joints or the neck thickness with the diameter of the clinch and compare it with the standards. Recently, Jaing et al. [54] used the variation of electrical resistance of the clinched joints and compared it to their strength to determine the quality of the joint. The non-contact optical method which is known as the digital image correlation technique can be used to investigate the ability of this method to detect the clinched joint defects during loading and unloading to inspect the quality of the joints without destructing the specimen.

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References

1. Israel M, Mauermann R, Schellnock J (2013) Thick sheet clinching: joining up to 20 mm total thickness. Adv Shipp Ocean Eng 2(1):1–10
2. Deutsches Reichspatent (1897) DRP-No. 98517 (in German)
3. Kaščák L, Spišák E (2012) Clinching as a non-standard method for joining materials of dissimilar properties. Zeszyty Naukowe Politechniki Rzeszowskiej Mechanika
4. Pietrapertosa C, Zhang L, Habraken A, Jaspart J-P (2003) Clinching joining system: validation of numerical models. In: 6th International ESAFORM Conference on Material Forming. Nuova Ipsa editire 351–354
5. Varis J (2006) Ensuring the integrity in clinching process. J Mater Process Technol 174(1):277–285
6. BOLLHOFF (2013) Devices and systems for joining sheets and profiles without fasteners. http://www.boellhoff.com/static/pdf/downloadcenter/EN/RIVCLINCH-EN-6780.pdf. Accessed 24 March 2015
7. Budde L (1994) Definition and Classification of Mechanical Fastening Methods. http://www.alueurope.eu/talat/lectuers/4101.pdf. Accessed 19 April 2015
8. Varis J (2003) The suitability of clinching as a joining method for high-strength structural steel. J Mater Process Technol 132(1):242–249
9. Gao S, Budde L (1994) Mechanism of mechanical press joining. Int J Mach Tools Manuf 34(5):641–657

10. Groche P, Wohletz S, Brenneis M, Pabst C, Resch F (2014) Joining by forming—A review on joint mechanisms, applications and future trends. J Mater Process Technol 214(10):1972–1994
11. Brani B, Benzegaou A (2014) Finite element analysis of the parameters affect the mechanical strength of a point clinched. Int J Eng Res Technol 2(8):795–799
12. Abe Y, Kato T, Mori K (2007) Joining of aluminium alloy and mild steel sheets using mechanical clinching. In: Materials Science Forum. Trans Tech Publ 1043–1046
13. Abe Y, Kishimoto M, Kato T, Mori K (2009) Joining of hot-dip coated steel sheets by mechanical clinching. Int J Mater Form 2(1): 291–294
14. Abe Y, Mori K, Kato T (2012) Joining of high strength steel and aluminium alloy sheets by mechanical clinching with dies for control of metal flow. J Mater Process Technol 212(4):884–889
15. De Paula A, Aguilar M, Pertence A, Cetlin PR (2007) Finite element simulations of the clinch joining of metallic sheets. J Mater Process Technol 182(1):352–357
16. Jayasekara V, Min KH, Noh JH, Kim MT, Seo JM, Lee HY, Hwang BB (2010) Rigid-plastic and elastic–plastic finite element analysis on the clinching joint process of thin metal sheets. Met Mater Int 16(2):339–347
17. Kim H-K (2013) Fatigue strength evaluation of the clinched lap joints of a cold rolled mild steel sheet. J Mater Eng Perform 22(1):294–299
18. Lee C-J, Kim J-Y, Lee S-K, Ko D-C, Kim B-M (2010) Parametric study on mechanical clinching process for joining aluminum alloy and high-strength steel sheets. J Mech Sci Technol 24(1):123–126
19. Mucha J (2010) The characteristics of H320LA steel sheet clinching joints. Adv Manuf Sci Technol 34(4):47–61
20. Mucha J (2011) The analysis of lock forming mechanism in the clinching joint. Mater Des 32(10):4943–4954
21. Hahn O, Tan Y, Schroeder M, Horstmann M (2005) Thermally supported mechanical joining of magnesium components. In: Materials Science Forum. Trans Tech Publ 365–370
22. Coppieters S, Cooreman S, Lava P, Sol H, Van Houtte P, Debruyne D (2011) Reproducing the experimental pull-out and shear strength of clinched sheet metal connections using FEA. Int J Mater Form 4(4):429–440
23. Mucha J, Kaščák L, Spišák E (2011) Joining the car-body sheets using clinching process with various thickness and mechanical property arrangements. Arch Civ Mech Eng 11(1):135–148
24. Lee C-J, Kim J-Y, Lee S-K, Ko D-C, Kim B-M (2010) Design of mechanical clinching tools for joining of aluminium alloy sheets. Mater Des 31(4):1854–1861
25. Zhao S, Xu F, Guo J, Han X (2014) Experimental and numerical research for the failure behavior of the clinched joint using modified Rousselier model. J Mater Process Technol 214(10):2134–2145
26. Carboni M, Beretta S, Monno M (2006) Fatigue behaviour of tensile-shear loaded clinched joints. Eng Fract Mech 73(2):178–190
27. Coppieters S, Cooreman S, Sol H, Van Houtte P, Debruyne D (2011) Identification of the post-necking hardening behaviour of sheet metal by comparison of the internal and external work in the necking zone. J Mater Process Technol 211(3):545–552
28. Coppieters S, Lava P, Sol H, Van Houtte P, Debruyne D (2013) Multi-axial quasi-static strength of a clinched sheet metal assembly. Exp Appl Mech 4:339–344
29. Gibmeier J, Rode N, Peng RL, Odén M, Scholtes B (2002) Residual stress in clinched joints of metals. Appl Phys A 74(1): 1440–1442
30. He X, Zhao L, Yang H, Xing B, Wang Y, Deng C, Gu F, Ball A (2014) Investigations of strength and energy absorption of clinched joints. Comput Mater Sci 94:58–65
31. Jomaa M, Billardon R (2007) Numerical analysis of the resistance to pullout test of clinched assemblies of thin metal sheets. In: 10th ESAFORM Conference on Material Forming. vol 1. AIP Publishing 169–174
32. Nong N, Keju O, Yu Z, Zhiyuan Q, Changcheng T, Feipeng L (2003) Research on press joining technology for automotive metallic sheets. J Mater Process Technol 137(1):159–163
33. Irfan Dost SAK, Aziz M (2012) Mechanical evaluation of joining methodologies in multi material car body. Int J Adv Eng Technol 5(1):259–268
34. Kaščák Ľ, Spišák E, Mucha J (2012) Evaluation of properties of joints made by clinching and self-piercing riveting methods. Acta Metall Slovaca 18(4):172–180
35. Lambiase F, Di Ilio A (2013) Finite element analysis of material flow in mechanical clinching with extensible dies. J Mater Eng Perform 22(6):1629–1636
36. K-i M, Bay N, Fratini L, Micari F, Tekkaya AE (2013) Joining by plastic deformation. CIRP Ann-Manuf Technol 62(2):673–694
37. Busse S, Merklein M, Roll K, Ruther M, Zürn M (2010) Development of a mechanical joining process for automotive body-in-white production. Int J Mater Form 3(1):1059–1062
38. Neugebauer R, Kraus C, Dietrich S (2008) Advances in mechanical joining of magnesium. CIRP Ann-Manuf Technol 57(1):283–286
39. Neugebauer R, Todtermuschke M, Mauermann R, Riedel F (2008) Overview on the state of development and the application potential of dieless mechanical joining processes. Arch Civ Mech Eng 8(4): 51–60
40. Mucha J, Witkowski W (2013) The experimental analysis of the double joint type change effect on the joint destruction process in uniaxial shearing test. Thin-Walled Struct 66:39–49
41. Liu FL, He XC, Zhao L (2014) A performance study of clinched joints with different material. Adv Mater Res 887:1265–1268
42. Zeng K, He XC, Deng CJ, Yang HY, Zhou S, Liu E (2014) An image-based method for automatic crack detection for the mechanical test of clinch joints. Appl Mech Mater 457:629–632
43. Jurkanin L (2013) Designing the tool for mechanical joining by tox-twin point method. Transfer Inovácií 26:141–144
44. Gerstmann T, Awiszus B (2014) Recent developments in flat-clinching. Comput Mater Sci 81:39–44
45. Balawender T, Sadowski T, Kneć M (2011) Technological problems and experimental investigation of hybrid: clinched-adhesively bonded joint. Arch Metall Mater 56(2):438–446
46. Sadowski T, Balawender T, Sliwa R, Golewski P, Knec M (2013) Modern hybrid joints in aerospace: modelling and testing/ Nowoczesne Połaczenia Hybrydowe W Lotnictwie: Modelowanie I Badania Eskperymentalne. Arch Metall Mater 58(1):163–169
47. He X, Gao S, Zhang W (2010) Torsional free vibration characteristics of hybrid clinched joints. In: Measuring Technology and Mechatronics Automation (ICMTMA), 2010 International Conference on. IEEE 1027–1030
48. Wen T, Wang H, Yang C, Liu LT (2014) On a reshaping method of clinched joints to reduce the protrusion height. Int J Adv Manuf Technol 71(9–12):1709–1715
49. Lee C-J, Lee J-M, Ryu H-Y, Lee K-H, Kim B-M, Ko D-C (2014) Design of hole-clinching process for joining of dissimilar materials–Al6061-T4 alloy with DP780 steel, hot-pressed 22MnB5 steel, and carbon fiber reinforced plastic. J Mater Process Technol 214(10):2169–2178

50. Ahn N-S, Lee C-J, Lee J-M, Ko D-C, Lee S-B, Kim B-M (2012) Joining high-strength steel and Al6061 sheet using hole clinching process. Trans Kor Soc Mech Eng A 36(6):691–698
51. He X (2010) Recent development in finite element analysis of clinched joints. Int J Adv Manuf Technol 48(5–8):607–612
52. He X, Liu F, Xing B, Yang H, Wang Y, Gu F, Ball A (2014) Numerical and experimental investigations of extensible die clinching. Int J Adv Manuf Technol 74(9–12):1229–1236
53. Lambiase F, Di Ilio A, Paoletti A (2015) Joining aluminium alloys with reduced ductility by mechanical clinching. Int J Adv Manuf Technol 77:1295–1304
54. Jiang T, Liu Z-X, Wang P-C (2014) Quality inspection of clinched joints of steel and aluminum. Int J Adv Manuf Technol 76(5–8): 1393–1402