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ORIGINAL ARTICLE

Recent and future development of the application of finite element analysis in clinching process

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Abstract Clinching is a mechanical joining method using a simple toolset consisting of a punch, a die, and a blank holder. The shapes of these tools are the most important parameters that control the final geometry of the clinch joints and consequently the strength and quality of the latter. In order to save time and cost, these geometric parameters could be optimized by the use of finite element simulation. This paper reviews the published research related to the finite element modeling of the clinching process. In this study, a critical review of the latter had been carried out from different perspectives. The findings about difficulties facing the simulations of different clinching processes, the optimization of the process parameters, and the strength, joinability, and the quality of the joint were highlighted. In addition, future development, investigation, and more research are still needed to minimize problems and expenses in the industrial practical application of clinching.

Keywords Clinching · Finite element method · Sheet metal · Joint strength · Optimization

1 Introduction

Mechanical joining techniques are widely used in different applications, such as automotive, aircraft, home appliances, and other industries. Lightweight structures are increasingly used in transportation in order to reduce weight, to save energy, and to reduce fuel consumption leading to less pollution and curbing of global warming. This can be achieved by the suitable selection of materials and efficient and appropriate joining methods. Traditionally, resistance spot welding is the prevailing connection technology for several industries' constructions. Due to technical issues, cost, time, pollution, etc., industries have begun to shift from traditional joining methods to mechanical joining methods such as clinching. The latter 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. Clinching has been known for 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 [1]. Just in recent years has the 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 [2]. Unfortunately, this process is still early in its development despite rapid advances in recent years; much more research is required to reach the point where accuracy, high quality, and optimal strength of the joints become comparable to industry 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.

Subsequently, a substantial amount of experimental studies has been carried out in order to understand the clinched joints. These experiments usually take too long to perform and are quite expensive when it comes to modifying tool geometry or material properties. To overcome these problems, the finite element (FE) method is frequently used [3].

A review paper on advancements of the finite element analysis (FEA) of clinched joints was published by He [4]. The

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author reviewed different works related to process, strength, and vibration characteristics of the clinched joints. The nonlinear problems exhibited by clinched joints consist of large deformations, material plasticity, and contact interactions. To cater for these difficulties, different numerical techniques (dynamic or static, implicit, and explicit methods) have been used when simulating the clinch forming process using different industrial simulation software (ABAQUS, ADINA, LS-DYNA, and MARC). The author believed that precise and dependable modeling of the clinched joint was still a complicated issue since the mechanical behavior of the joints depends not only on the geometric characteristics of the joint but also on the process parameters. Relevant articles and research into the FEA of the clinching joining process are very limited. The research and development in this field are still slow because of the complexity of the process [4].

Therefore, this article critically summarizes the published efforts of recent years toward improving the knowledge of the clinching connections using the finite element (FE) method to simulate the different types of clinching processes, to predict the strength of the clinch joints, and to optimize the main parameters that affect the clinching process. Some important modeling issues that still need further investigation are discussed in order to provide a basis for further research.

2 Clinching process

The clinching process is commonly used in automotive joining. It simply includes a set of tools (punch and dies) by which the clinched joints can be created using different materials. The process sequence, described by four steps, is illustrated in Fig. 1 [5]:

- The punch and blank holder move downward; the work pieces are clamped and fixed by the spring force of the blank holder.
- By action of the punch, the material flows into the bottom die cavity forming a cup. The process parameters and dimensions of the punch and die are finely tuned to the sheet thickness of the work pieces. This insures that no material is laterally drawn into the joint from the surrounding area.
- Finally, the thickness of the cup's bottom is reduced by upsetting, and the material forced into the die groove and in lateral direction, forming the necessary undercut.
- After reaching a predetermined maximum force or a predetermined displacement, the punch is retracted and the clamping force relieved. The joint connection requires no finishing.

Clinching consists of two principal actions, forming and drawing, that cause the creation of the interlock between the layers of metal sheets. 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. Furthermore, the size of the tools and friction coefficient are some of the major factors that influence the clinching joint as illustrated in Fig. 2 [6].

There are different procedures and tests to determine the quality of the clinching joints [7, 8]. 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. Rietman et al. [9] applied the standardized tests for spot welding, namely the tensile test where the joint is tested in the clinching (axial) direction, and shear test in a transverse direction as shown in Fig. 3.

3 Finite element simulation of the clinching process

The finite element method originated from the need to solve complex and sophisticated structural analysis problems in different engineering and non-engineering fields. Since the clinching process is considered as a complex cold metalworking process, it obviously needs complete accurate information and knowledge of different parameters, such as the materials and friction behaviors, to obtain a sufficiently precise FEA simulation. Published work relating to the FEA of clinched joints was reviewed in terms of commercial software used, element used, material thickness, and type. It is indicated that the finite element analysis of clinched connections will help future applications of clinching. Using the finite element method (FEM) to optimize process parameters will give the

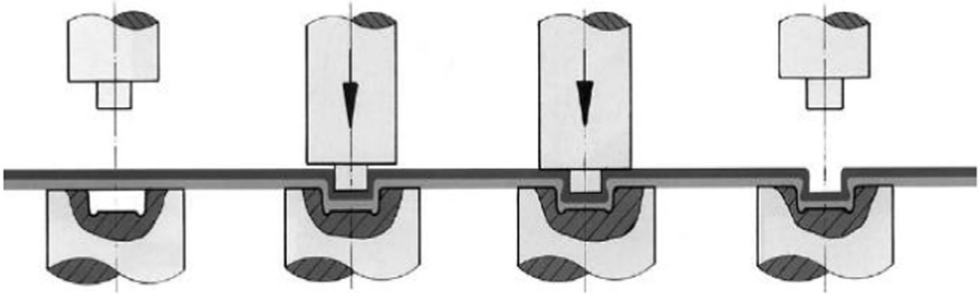


Fig. 1 Single-step clinching without cutting [5]

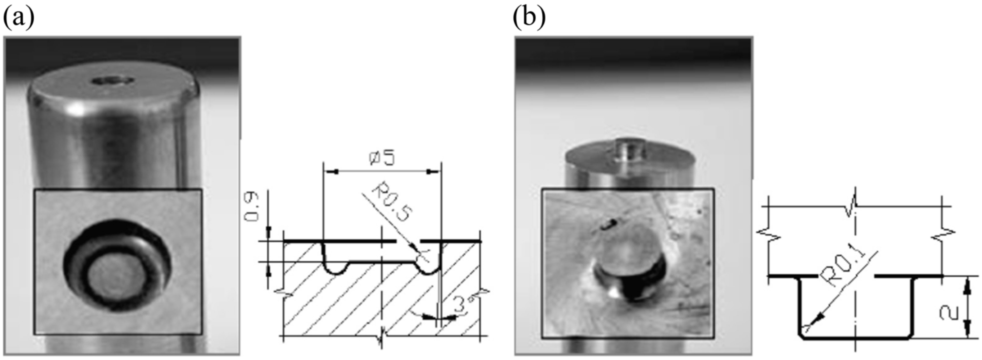


Fig. 2 An example of main dimensions for punch and die. **a** The die, **b** the punch [6]

process a greater joint manufacturing success rate. In addition, FEM will facilitate many experiments and tests that would take too long to perform or cost a lot in the actual application. Furthermore, the use of FEA simulation will reduce the time and cost and increase joint quality, strength, and manufacturing. Table 1 summarizes some of the main publications in FEA of the clinching process.

Eckert et al. [10] used a 2D simulation approach to predict the deformation resulting from the mechanical joining process. The results showed why 3D models are infrequently used: due to solver time even with the use of high-performance computers. Moreover, the investigation illustrated the lack of published work focused on the validation of the distortion prediction by FEM. DEFORM finite element commercial software, developed especially for the forming process, was utilized. The authors used the ECKOLD clinching machine parameters (blank holder diameter, spring stiffness, and die diameter) in their simulation.

3.1 Fixed die clinching

The first study using the finite element analysis was conducted by Hamel et al. [11]. They developed a devoted, fast, and effective finite element code for studying clinch forming and validated their model with the use of two numerical approaches: the static explicit and the static implicit methods using ABAQUS commercial software. Generally, the results indicated that using a static explicit scheme would be an efficient and quick numerical approach to study and simulate the clinching process. The significance of their study is the utilization of the numerical approach to investigate the effect of friction and strain hardening on their model. They concluded that these parameters play major role in the process. Figure 4 illustrates the effect of different friction values on the bottom thickness of the final geometry of the joint.

Jayasekara et al. [12] investigated the clinching of AA 5754 metal sheets using rigid-plastic and elasto-plastic models with Coulomb friction and a constant shear friction. The process simulation was carried out using an axisymmetric model in FE commercial software, DEFORM-2D. The FEA results showed that there is no major difference between the two models of friction for large deformation of thin metal sheets.

Pietrapertosa et al. [13] developed a numerical method, with the use of FEM code (LAGAMINE) that simulated the clinching forming process. The work opened a new horizon to the analytical formulation of the behavior of clinched joints. Regrettably, the model was not able to simulate the clinch forming operation very well. A purely numerical publication was conducted by De Paula et al. [14]. The authors used an updated Lagrangian finite element approach and the 2D quadrilateral element of DEFORM™-2D software to simulate several types of punch and die geometries for the clinching process. Since the simulation results were not validated with experimentation, the study showed very little information on the metal flow. However, it was found that a partially conical die and a decreased ring groove depth would increase the possibility of the creation of an interlock.

In addition, two different studies were performed by Coppieters et al. [15, 16] using an ABAQUS software axisymmetric 2D model and a 3D model. The 2D axisymmetric model used CAX4R elements with reduced integration and hourglass control. The 3D model used C3D8R elements.

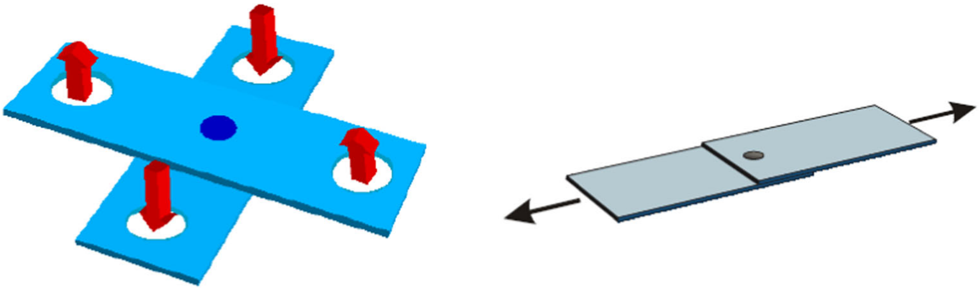


Fig. 3 Tensile test and shear test [9]

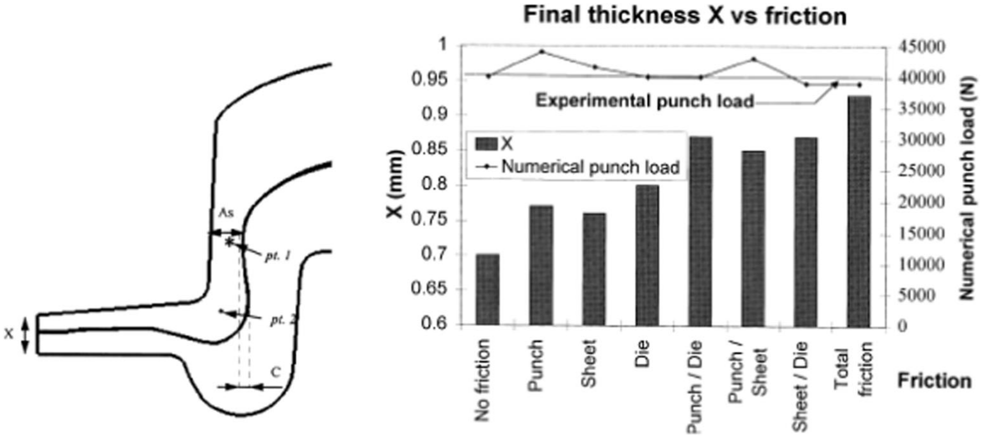
Table 1 Summary of the research trends in FEA of the clinching process

Author	Year	Commercial software	Methods/scheme	Elements used	Model description	Tool type	Material type	Thickness	Test
Hamel et al. [8]	2000	ABAQUS	Implicit and explicit scheme, reduced integration with hourglassing control	4-node axisymmetric 3- and 6-node triangular element	Elastic–plastic model	Tog-L-Loc 5.2 mm TOX	Extra mild isotropic steel and high-strength steel	1.0 mm	Tensile test and cross shear test
Rietman et al. [47]	2001	INDEED®	Implicit scheme	Isoparametric bilinear quad and tri-linear brick element	Elastic–plastic model 2 D	Tog-L-Loc 5.5 mm TOX 6.0 mm	DC04 and DC06 deep drawing steel	1.2 mm 0.8 mm	Tensile test and shear test
Pietrapertosa et al. [9]	2003	LAGAMINE	Large strain	3D elements in large strain (element JET3D in LAGAMINE contact element called CFI3D)	Elastic plastic 3D	Round	Two steel grades: S235 and S350	0.2–0.4 mm	Shear tests Tensile tests
Paula et al. [10]	2007	DEFORM™-2D	Updated Lagrangian finite element approach	2D quadrilateral element	Purely plastic axisymmetric problem	Round	Aluminum alloy 1100	0.5-mm thickness each	No experiments
Coppieters et al. [11]	2007	ABAQUS commercial software	An axisymmetric (2D) model and a 3D model)	Axisymmetric model contains CAX4R elements. These are 4-node bilinear rectangular elements using reduced integration with hourglassing control 3D model uses C3D8R elements	Elasto-plastic material modeled to be isotropic	Round and rectangular TOX	ZStE 340 and DC05	1.0 and 1.5 mm	Pullout and the shear strength
Coppieters et al. [12,48]	2011	ABAQUS commercial software	2D axisymmetric and a 3D finite element model	The 3D models 8-node linear bricks with reduced integration and hourglass control are used.	Elasto-plastic material	TOX round	DC05	1.12 mm	Shear strength Pullout strength box test
Abe et al. [26]	2009	LS-DYNA	Axisymmetric plastic deformation	Quadrilateral solid elements	Elasto-plastic	Round	Hot dip steel sheet	1.2 mm	Tensile and shear test
Mucha [13]	2010	MSC program; Marc Mentat 2007	Updated Lagrangian formulation (ULF)	10 quadrilateral axisymmetric elements	Elasto-plastic material model	Round die	H320LA sheet plates	1.0 mm	Tensile and cross shear test
Mucha [15]	2011	MSC; Marc	Updated Lagrangian formulation elastic–plastic material	Elastic–plastic material model, using a type 10 quadrilateral axisymmetric element	The large elasto-plastic deformation process	Round die TOX	H320LA	t=1 mm	Tensile test Shear test Micro-hardness measurement
Abe et al. [27]	2012	Commercial finite element code LS-DYNA	Elastic–plastic material	Axisymmetric quadrilateral solid elements	Large plastic deformation	Round die	High-strength steel sheets (SPFC780 and SPFC980) Aluminum alloy sheets (A5052)	Thickness range 1.4–1.6 mm	Tensile test Shear test
Benabderrahmane et al. [16, 49]	2013 2012	Static explicit and the static implicit (ABAQUS) and An elasto-plastic incremental finite element computer code baptized SEMA	Static explicit method analysis updated Lagrangian formulation	Quadrilateral elements Q4 axisymmetric	Large elasto-plastic deformation	BTM TOX	Steel sheets ES	1.5 mm	Tensile test Shear test
Mauermann et al. [17]	2013	Not shown	Not shown	Axially symmetrical FEA model	Elasto-plastic	TOX round	Steel sheets S380 into S235 S235 into S235	6.0 mm 4.0 mm 5.0 mm 5.0 mm	Tension test Static strength Fatigue strength
Oudjene et al. [42]	2008	ABAQUS/Explicit	An axisymmetric model with a dynamic explicit approach Taguchi DOE	A quadrilateral axisymmetric element (element CAX4R) involving 808 elements	Elasto-plastic	TOG-L LOC TOX	Aluminum alloy AL5754	0.5 mm thick	Tensile and shear loading test
	2007	ABAQUS/Explicit			Elasto-plastic	TOG-L LOC		0.5 mm thick	

Table 1 (continued)

Author	Year	Commercial software	Methods/scheme	Elements used	Model description	Tool type	Material type	Thickness	Test
Oudjene et al. [41–43]	2008 2009		An axisymmetric model with a dynamic explicit approach The response surface method and SQP algorithm	A quadrilateral axisymmetric element (element CAX4R) involving 808 elements		TOX	Aluminum alloy AL5754		Tensile and shear loading test
Lambiase et al. [6]	2013	Not shown	A 3D finite element model elastic–plastic material model with an isotropic material	8-node linear elements with reduced integration	Elastic–plastic material model	TOG-L LOC TOX	AISI 1010 sheets	Nominal thickness of 1.0 mm	Tensile test
Jomâa et al. [20, 21]	2007	ABAQUS	3D explicit or implicit scheme (discrete rigid R3D elements)	Linear solid elements (4-node CAX4R in ABAQUS) and 8-node C3D8R elements	Elasto-plastic	TOX round	2 different steels and the aluminum alloy	Die side, td Punch side, tp, 2.0 mm 1.0 mm 0.8 mm	Pullout test Shear test
Mori et al. [22]	2007	Commercial finite element code LS-DYNA	Quadrilateral solid elements	Axisymmetric deformation	Large plastic deformation	Round	Aluminum alloy sheet A5052-H34 high-strength steel sheets SPFC440, SPFC590 and SPFC980	1.4 mm 1.5 mm	Uniaxial tensile and compression tests Cross-tension test
Saberi et al. [23]	2008	ABAQUS/Explicit	Explicit scheme	Anisotropic plasticity	Large Plastic deformation	TOX round	Commercial steel H180Y	(0.60–0.35 mm)	Shear tension tests
Kim [24]	2013	ABAQUS software (version 6.6) for the solver and Hyper Mesh software (version 7.0) as the pre- and post-processors		HEXA element (C3D8) and a PENTA element (C3D6); 48,420 nodes and 42,956 elements	Elasto-plastic	TOX	Cold rolled mild steel (SPCC)	0.8 mm both sides	Tensile-shear test and fatigue tests
Lee et al. [39, 40]	2010	DEFORM-2D	Not shown in the study	Not specified in the study	Elasto-plastic	TOX round	Advanced high-strength steel DP780 and Al5052 Aluminum alloy sheet Al6063	Thickness 1.6 mm St 2.0 mm Al	Tensile test—H-type
Coppieters et al. [33]	2013	ABAQUS/Explicit	A hypo elastic–plastic constitutive model	4-node bilinear rectangular elements using reduced integration and enhanced hourglassing control element size of (*t*) sheet thickness /15	A hypo elastic–plastic	Round	Deep drawing mild steel DC05	1.15 mm Both die and punch side	Tensile test (box test)
Roux et al. [44]	2013	Finite element software Forge2009 mixed Velocity–pressure formulation	Euler scheme is used for the time integration	Asymmetrical assumptions Isoparametric linear tetrahedrons and a bubble function is added in order to satisfy the stability condition of Brezzi/Babuska	Large plastic strain	Round	Both sheets aluminum alloy 5774	Upper sheet 1.0 mm and lower sheet 1.5 mm	Tensile test ARCAN setup mechanical strength
He et al. [25]	2014	LS-DYNA	Lagrange method and r-self-adaptively	(2D axisymmetric model)	Piecewise-linear plasticity material model which adopts the Cowper–Symonds	RIVCLINCH 1106 P50	Aluminum alloy 7075 w	2 mm thickness	Tensile and shear mechanical test
Wen et al. [45]	2014	DEFORM-2D	Large plastic deformation—Lagrange	2D–Axisymmetric	Clinching and reshaping are typical elastic–plastic	Not specified	Al6063	0.8 mm	H-type tension test model for pullout strength
Zhao et al. [46]	2014	ABAQUS	Modified Rousselier model	A plane stress 2D model 3D model uses C3D8R elements	Elastic–plastic	Not specified	Al5052-O sheets	Thickness of 2 mm	Tensile and shear tests

Fig. 4 Final thickness *X* versus friction [11]



The metal sheets used in the experiments were DC05 (1.5–1.12 mm thickness) and ZStE340 (1.0 mm thickness). The friction coefficient was assumed to be 0.15 using Coulomb's law. In addition, the loads assigned for each model consisted of the clinch operation, the subsequent elastic springback, and the mechanical loading of the clinched joint. The study showed the advantage of having more elements through thickness and the capability of predicting the resistance of the clinched connections as shown in Fig. 5. Furthermore, the obtained results indicated that FEM is capable of simulating the forming operation despite the existence of some discrepancy between the experiment and the simulation.

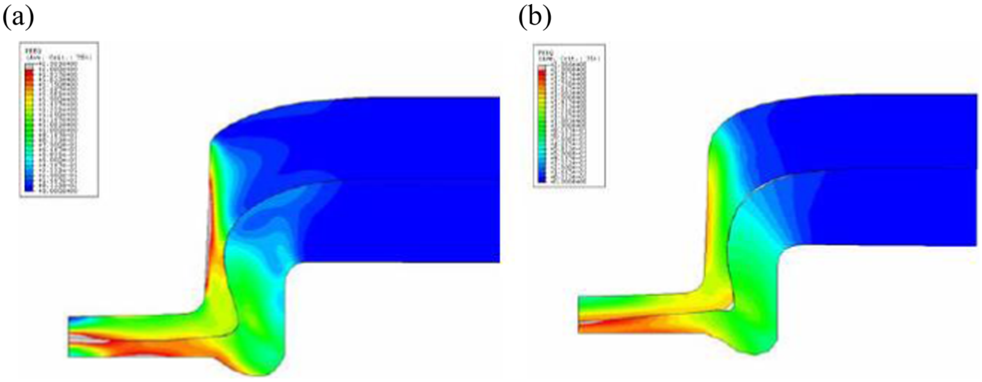
Mucha [17] studied the clinch joining forming process of a high-strength low-alloy thin sheet metal (H320LA) numerically and experimentally. The updated Lagrangian formulation using a type 10 quadrilateral axisymmetric element of MSC Marc software was used for the numerical simulation of the large elasto-plastic deformation. The study showed that the die geometrical parameters are the most important factors influencing the plasticity of the material flow, the lock shape parameters, and energy consumption of the joint connection as illustrated in Fig. 6. A good agreement between the experiments and the FEA results for the joints was achieved as shown in Fig. 7.

In a subsequent study, Mucha [18] showed that the change of shape and size of the die groove influenced the forming force and the velocity of material flow affecting the interlock creation between the sheets as depicted in Fig. 8 [18].

Abe et al. [19] used the commercial software LS-DYNA to simulate the mechanical clinched joint of hot dip galvanized thin sheets. An axisymmetric quadrilateral solid element was used for modeling the clinching process where the punch, die, and the blank sheet holders were assumed to be totally rigid. The simulation results agreed with the experimental ones as described in Fig. 9. It can be seen that there is a small effect of the zinc layer on the quality of this cold joint. Additionally, the galvanized layer thickness of the sheet was decreased in different locations such as the punch side face and the die walls. Furthermore, authors performed modifications for the tool geometries to control and minimize the reduction of the layer thickness after forming the joint.

An investigation study of joining aluminum alloy sheets (Al6063) by mechanical clinching technique was presented by Lee et al. [20]. They developed analytical and numerical approaches which were validated by experiments. The FEA was accomplished using the commercial software DEFORM™-2D. The tools of the clinching process were assumed to be totally rigid. The friction coefficient was assumed to be constant between the two sheets with a value of 0.4 whereas the value between the sheets and the tools was 0.12.

Fig. 5 Equivalent plastic strain fringe with different elements configuration (**a**) 10 and (**b**) 5 elements through sheets thickness. [16]



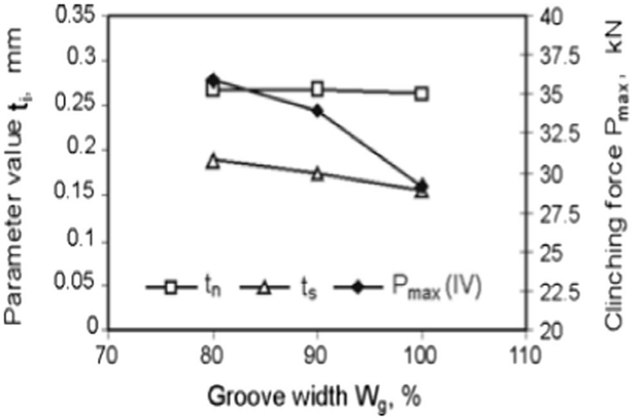


Fig. 6 The influence of proportional groove width on the lock thickness (t_s) and neck thickness (t_n) with relation to maximum forming and drawing force (P_{max}) [17]

The design of the experiment method was used to perform different combinations of the shape parameters of the process. The simulation results compared with the geometry function values and the experiment's results presented a good agreement with 7.47 % dimensional error. The FE analysis and the experiment's results were utilized to evaluate the joint's strength and quality, such as the neck thickness and the undercut length [20].

3.2 Extensible die clinching

Due to some limitations with fixed die clinching, extensible die clinching had been developed in recent years. It bears many advantages especially the easiness to remove material from the die thereby increasing the process readiness for automation. In addition, it produces joints with high pullout tension values due to improved flow behind the material because the die opens during clinching and the material can flow to the side [21].

Zheng et al. [22] outlined a procedure and programmed a code to simulate the extensible die clinching using the finite element method. This research illustrated the material flow pattern of the conventional clinched tool (fixed die) compared to the extensible one. Furthermore, the extensible die groove, depicted in Fig. 10, was studied in more detail by Lambiase et al. [23, 24]. They used a 3D finite element elastic–plastic material model with isotropic material and eight-node linear elements with reduced integration to investigate the clinching process and to optimize the clinching tools to increase the clinched joints' strength. An elasto-plastic scheme was used, and a 3D model with one plane of symmetry was developed to study the influence of the process parameters and to analyze the material flow during the joining process. Figure 11 shows the material flow from various sheet thicknesses toward the die. In addition, to reduce the localization and amount of the plastic strain, the clinching tool set geometry was modified and heat was introduced to the aluminum sheets in order to reduce the ductility for better joinability [25].

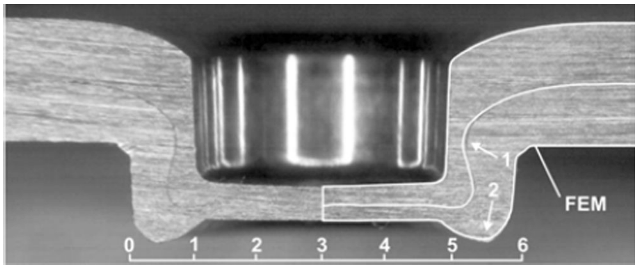


Fig. 7 Comparison between numerical results with a cross section of the clinched joints [17]

He et al. [26] studied the extensible die clinching process numerically using FEA commercial software LS-DYNA for a clinching joint both with and without adhesive. The axisymmetric nature of the clinching process allowed generating a 2D axisymmetric model based on the Cowper–Symonds material models. An implicit technique with the Lagrange method and r-self-adaptivity was introduced to the 2D model. The element Solid 162 was used. Moreover, the large deformation with high plastic strain involved in both the fixed and in the extensible die clinching processes caused severe local mesh distortion. To alleviate this problem, the ALE adaptive technique was used. Furthermore, ASS2D single contact function was used to model the contacts between the surfaces of the tools and the blanks. Figure 12 illustrates the simulation steps for the extensible die of the clinching process.

The results of the study showed that the hybrid clinched joint has more strength than the one without adhesive, and the results from simulation agreed with the experimental results as shown in Fig. 13.

3.3 Dieless clinching

Dieless clinching is an alternative clinching technology that works with a flat anvil as a counter tool rendering possible the joining of materials having limited formability at room temperature. Gerstmann et al. [28] used MSC Marc element type 10 which is a four-node isoparametric element for axisymmetric analysis. The element stiffness is calculated by the four-point Gaussian integration approach. The simulation determined that the use of the 3D full model is unsuitable due to the huge number of elements needing long computing time compared with the 2D axisymmetric model. This study showed not only the possibility of joining metals but also the capability of connecting plastic, polyester, and other dissimilar materials using flat clinching without any additional material between the two sheets.

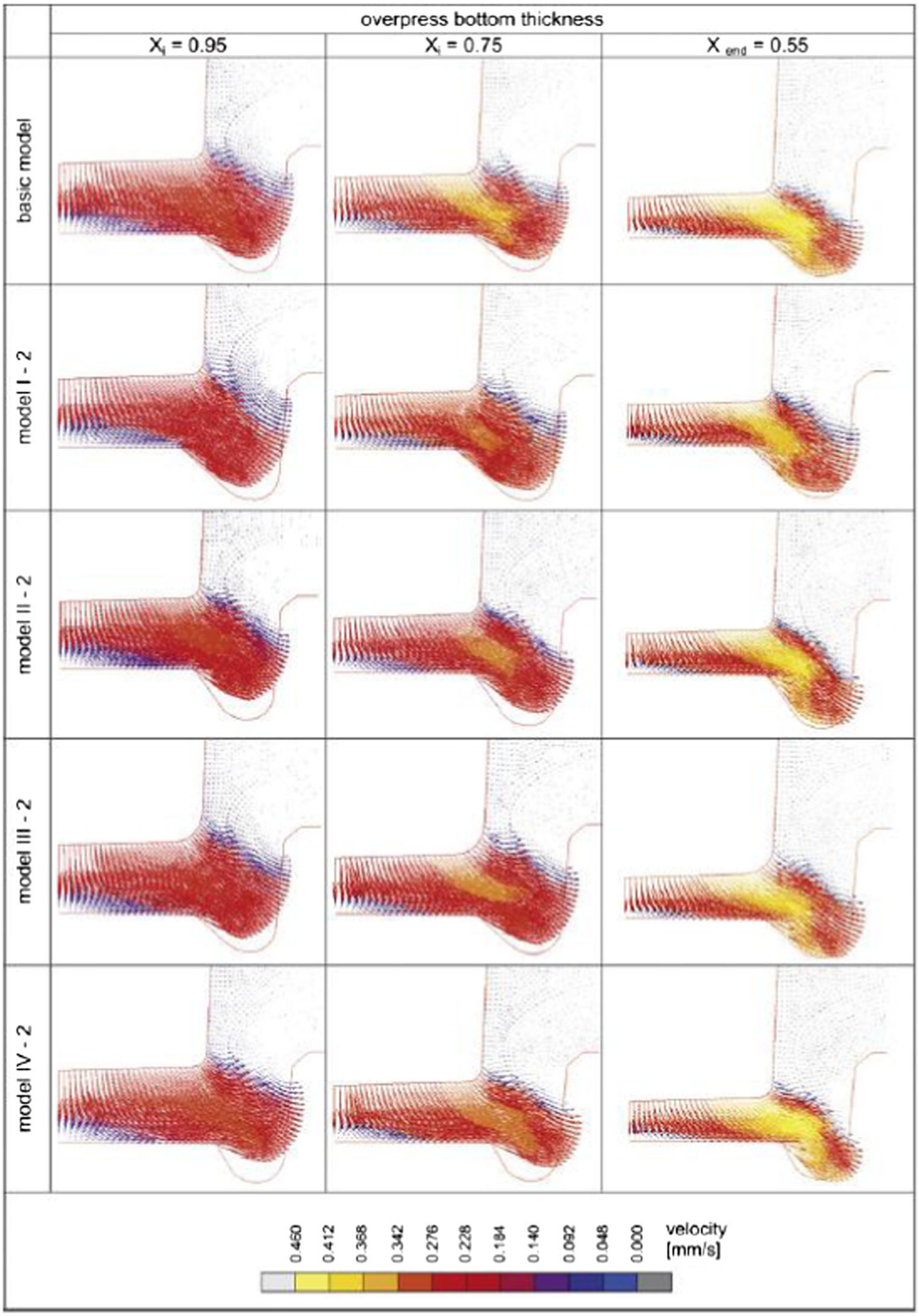


Fig. 8 The shape effect of the die on the material flow related to X sheet bottom thinning values [18]

Furthermore, the flat clinching process for joining magnesium was modeled and simulated by using DEFORM-2D software with an automatic remeshing enhancement due to the large deformation nature [29, 30]. The tools of the mechanical connection process were assumed to be rigid during the simulation. It was found that the factor with the greatest effect in the dieless clinching process is the punch geometry, especially the punch edge radius. Furthermore, the results showed a relationship between the punch diameter and the neck thickness as well as the interlock length [29, 30].

A study conducted by Han [31] showed the possibility of joining a magnesium alloy plate using the mechanical clinching technique. FE simulation commercial software DEFORM-2D with adaptive remeshing to the area with large deformation was used. The data obtained from the simulation revealed that the resistance and the quality of the joint can be

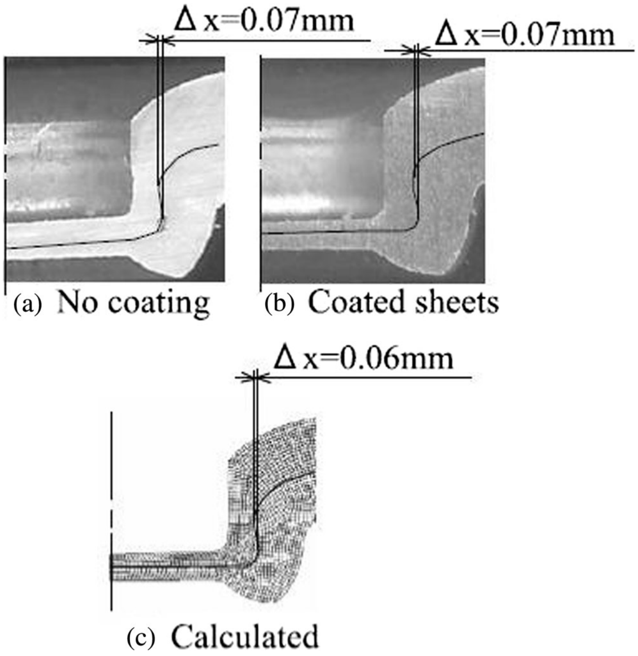


Fig. 9 Interlock length values obtained from experiment compared to numerical calculated values [19]. **a** No coating. **b** Coated sheets. **c** Calculated

optimized by calibrating and controlling the die parameters (die depth, groove width, and draft angle).

3.4 Hole clinching

Hole clinching was developed to join materials such as aluminum alloy to high-strength/low-ductility materials. In this process, the ductile material is positioned uppermost and the brittle material into which a hole is formed is positioned below that. The upper sheet is indented into a die cavity through the hole in the lower sheet and spread so that the two sheets interlock geometrically [32]. Hole clinching was simulated using DEFORM-2D software where the design of the die was created based on the geometrical relationship as illustrated in Fig. 14. The results demonstrated that FE was able to effectively simulate the hole-clinching process for joining dissimilar materials. Indeed, FEA was used to estimate the shape of the geometrical parameters affecting the clinching joints such as interlocking length and neck thickness. Moreover, the final shape of the hole-clinching tools was obtained from the simulation of the process, leading to a joint free of defects.

3.5 Hybrid clinching

In general, there is very little knowledge that can be found on hybrid clinching technology. Balawender et al. [33] and Sadowski et al. [34] had performed a numerical and experimental survey of clinch-adhesive hybrid joints. The hybrid joining of dissimilar materials is a modern and innovative technology allowing the joining of different material densities with appropriate strength. This process aims to establish durable and reliable lightweight assemblies. Its practical implementation in the industrial and research fields is still limited and needs more investigation and research, especially to examine the strength of the traditional and hybrid connection strengths, characteristics, and properties. The overlap combined joint, using adhesive with clinching, was studied by FE ABAQUS code and experimentation. The results indicated that the clinched joint before adhesive curing was stronger [33, 34].

He et al. [27] investigated the energy absorption and the maximum load of the conventional clinching joints compared to the hybrid clinching joint. They found that the energy absorption and the maximum load of the hybrid joint are higher than the conventional one as seen in Fig. 15. Finally, good agreement between experimental and numerical results was obtained.

3.6 Strength of the clinch joints

A finite element method within the commercial program ABAQUS was used by Benabderrahmane et al. [35, 36] to evaluate the mechanical strength of clinched joints for 1.5-

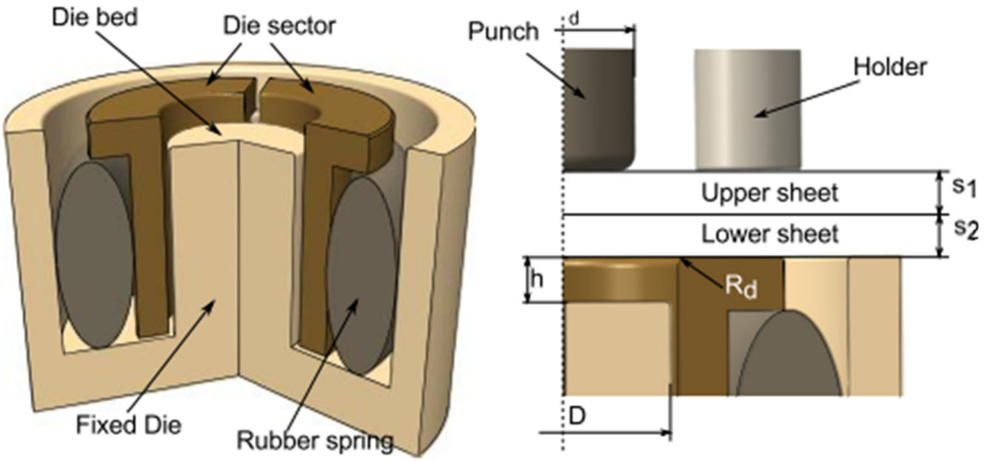
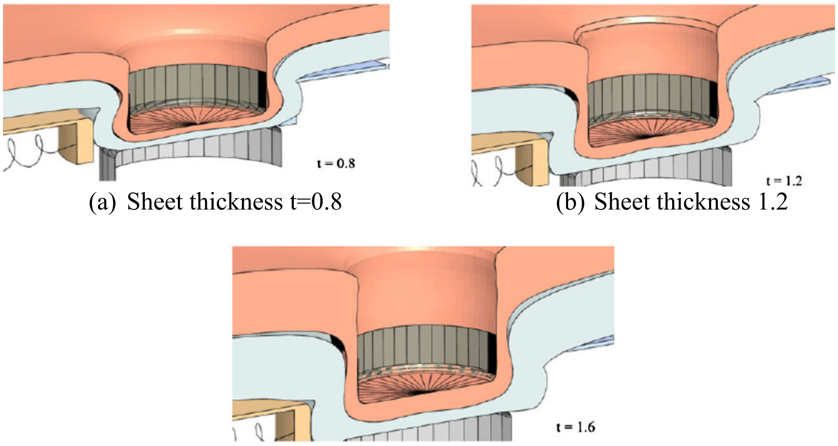


Fig. 10 Extensible clinching machine with tools configuration [23]



(a) Sheet thickness t=0.8 (b) Sheet thickness 1.2

(c) Sheet thicknes t=1.6

Fig. 11 Flow of the material toward the extensible die with various sheet thicknesses [24]. **a** Sheet thickness $t=0.8$. **b** Sheet thickness $t=1.2$. **c** Sheet thicknes $t=1.6$

mm-thick steel sheets. They performed static explicit and static implicit methods using quadrilateral Q4 axisymmetric elements. The results showed a good agreement with experiments at the geometric level. In addition, the punch force related to different sheet thicknesses was calculated and improved to an acceptable level. Moreover, the geometry of the tools and friction were considered as important parameters that affect the formation of the clinched joint and its mechanical strength. The study gave insight for future work through the development of the computer code, including remeshing, taking into account the damage variables to predict the clinching of the point and the implementation of the extended finite element methods. Israel et al. [37] carried out a FEA where the metal sheets were modeled as elasto-plastic and the material properties values and functions were obtained using a universal tension testing technique. Verification between FEM and the results of the tests showed some deviation. This might be due to the sheet production tolerance (sheet thickness, strength), which leads to different output as described in Fig. 16. For more sensitive and accurate clinching simulation results, authors used varying parameters. The results of the study indicated that clinching for thick sheets is possible for material tensile strength up to 700 MPa [37].

Traditionally, the mechanical behavior of clinched joints is examined by a pullout test and a single shear lap test. Jomâa et al. [38, 39] presented a FEA using ABAQUS code (elasto-plastic model, explicit/implicit scheme, linear solid 4-node CAX4R and 8-node C3D8R elements). The researchers also introduced the joint fracture using a damage model. Figure 17 illustrates the failure of a clinch joint to pullout tests and shear tests. A study conducted by Saberi et al. [40] employed ABAQUS commercial software in an explicit scheme to simulate single shear lap tests on the clinching process.

The joining of ultra-high-strength steel (SPFC440, SPFC590, and SPFC980) and aluminum alloy sheets (A5052-H34) with thicknesses of 1.4 and 1.5 mm was investigated by Mori et al. [41] using mechanical clinching and self-piercing rivets. The clinching joining process was designed from trial and error with the power of FEM simulation (LS-DYNA). The results showed that the problem of different melting points for the aluminum and steel sheets is overcome by cold joining. However, joining of high-tensile-strength

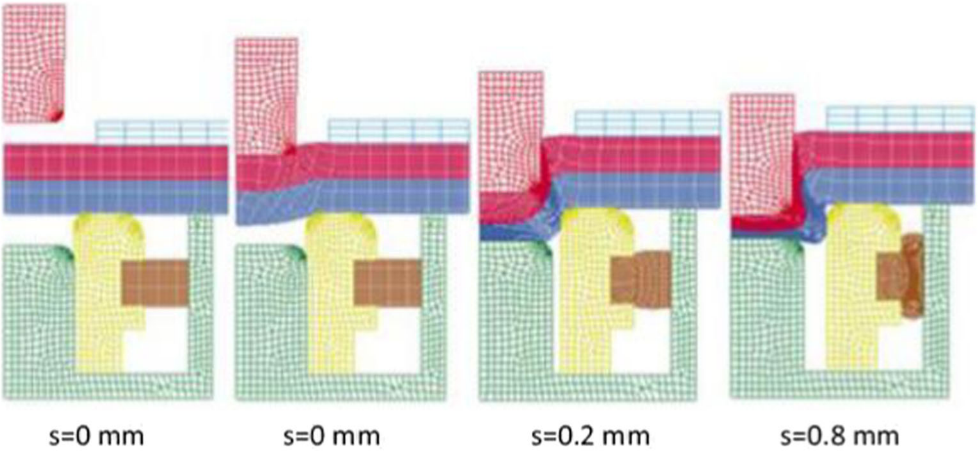


Fig. 12 The simulation steps for the extensible die of the clinging process [26]

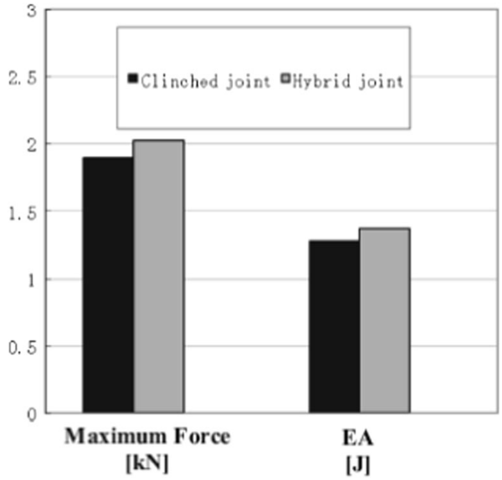


Fig. 13 Comparison between the clinching joint strength and energy absorption for conventional joint and hybrid joints using the extensible die [27]

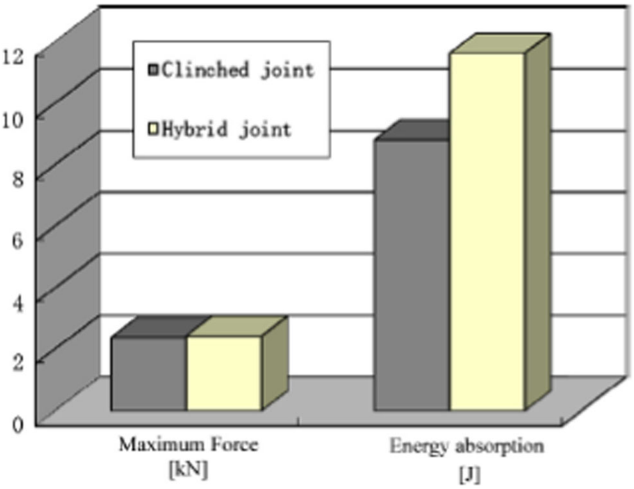


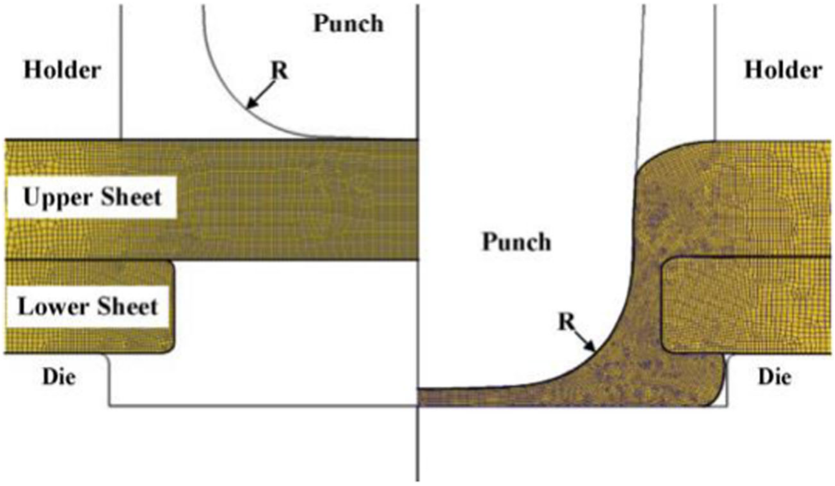
Fig. 15 Shows the energy absorption and the maximum load of the conventional clinching joints compared to the hybrid clinching joint [27]

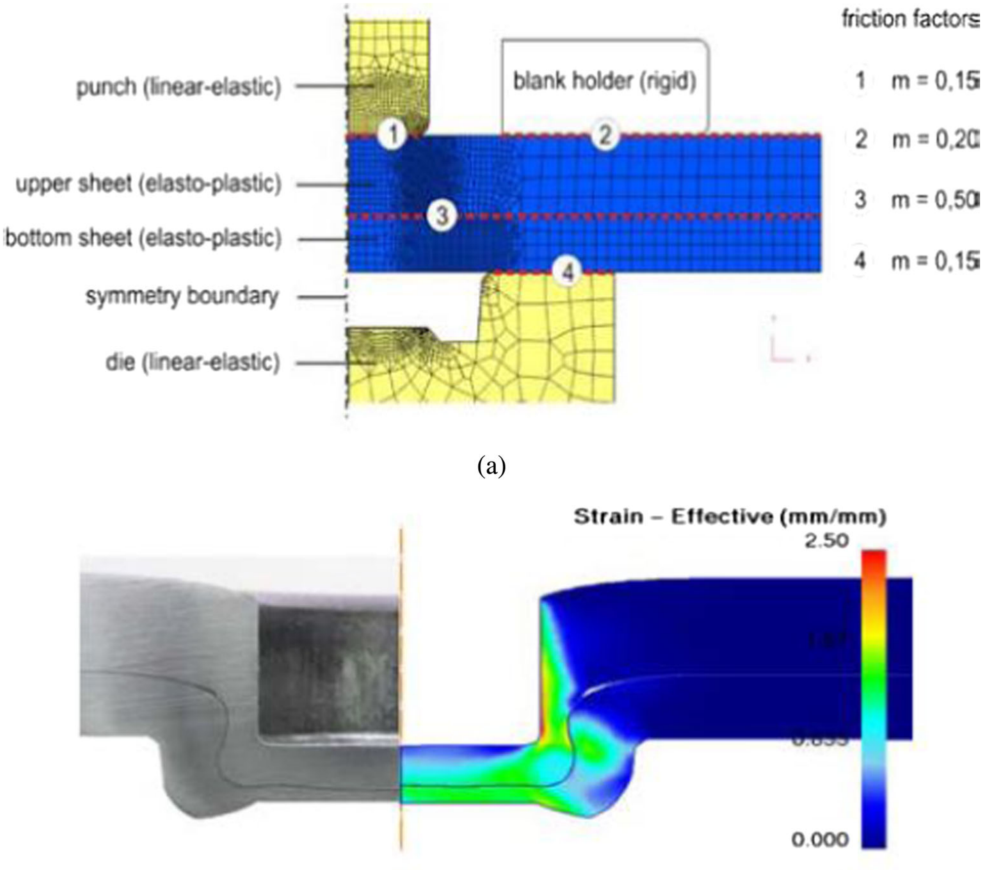
sheets makes the plastic joining difficult. Furthermore, the optimization of the die by FE simulation was used without changing the mechanical properties of the sheets or the materials used for joining. Finally, researchers found that the mechanical clinching and self-pierce riveting are efficient and suitable for connecting steel and aluminum alloy sheets in different applications. The numerical simulation results of pullout and shear tests have been validated by the experimental results. Authors believe that clinching joint simulations with the two tests still needs to be investigated and the material damage and failure must be taken into account. Also, it still needs validation and sensitivity studies.

Kim [42] presented a study about evaluating the fatigue strength of the clinched lap joint. FEA was performed using ABAQUS where two different elements (HEXA (C3D8) and PENTA (C3D6) elements) were implemented to create the model. The outcome of the simulation at the fatigue endurance limit showed that there is a similarity of the two values of the Von Mises stress and the ultimate tensile strength of the used materials (mild steel sheets). This indicates that the hardness of the mild steel is improved at the neck area due to the cold work during the clinching joining process as shown in Fig. 18.

Recently, a computational 2D axisymmetric model using LS-DYNA was established by He et al. [27], illustrated in Fig. 19, to simulate the clinching process 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 forming, elements may become severely distorted leading to non-accurate results. Kill elements technique was therefore used to eliminate and dismantle the damaged elements. In addition, an implicit technique with Lagrange's formulation and r-self-adaptive remeshing were used. The friction coefficients were found to strongly influence the quality of the joint. Because of the lack of experimental data

Fig. 14 Axisymmetric model for the designed hole-clinching process [32]





(a)

(b)

Fig. 16 Clinching simulation of thick metal sheet. **a** Axisymmetric model. **b** Comparison of numerical effective strain and cross section results to experimental ones [37]

available, friction was assumed to be governed by Coulomb's law. Figure 20 shows good agreement between the 2D-numerical results and the experimental ones.

Moreover, a 3D model was used to simulate the tensile-shear test using ANSYS 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 as described in Fig. 21.

Coppieters et al. [43] investigated and simulated the multi-axial quasi-static strength of a clinched sheet metal assembly. The study presented the development of an Arcan-like device which allows the use of different shear and tensile ratios in clinched metal sheets in order to predict the strength of the joints. The simulation was conducted using ABAQUS explicit scheme with the linear eight-node brick element, enhanced hourglass control, and reduced integration. The simulation results showed that the shear-to-tensile ratio was drastically affected by the ductility and the ultimate resistance of the joint. The load directions were applied with different angles from 0° up to 90°. The analysis of the deformation mode showed that the strength of the joint increased for angle values between 45 and 90° (Fig. 22). Moreover, the frictional behavior and the post necking were considered as one of the important factors affecting the clinching forming and the quality of the joint. The outcome of this study opened new horizons for more research on crack propagation and to the development of failure criteria for clinched joints under multi-axial loading [43].

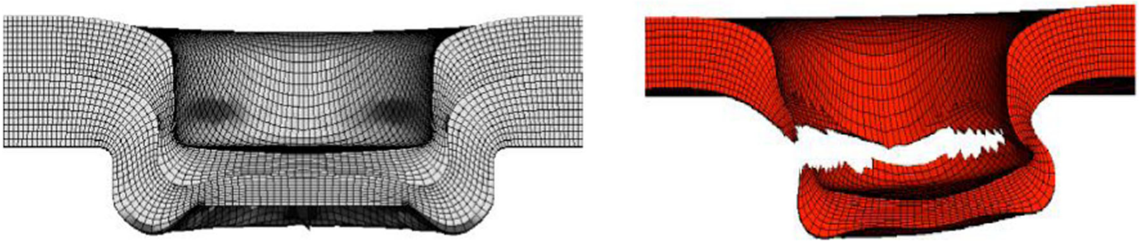


Fig. 17 Failure in the upper sheet in the neck area due to the high localized area [40]

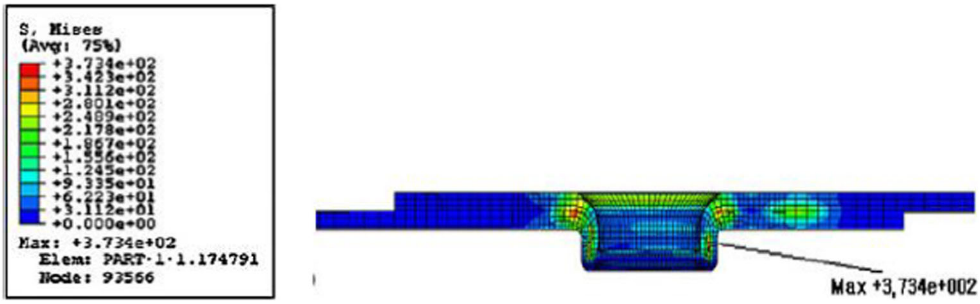


Fig. 18 Maximum Von Mises stress at the fatigue endurance limit is around 373 MPa where the ultimate tensile strength is 382 MPa for mild steel [42]

3.7 Optimization of the clinching process

Different studies had focused on optimizing the clinching tools to obtain the higher possible strength of the joint. Oudjene et al. [44] attempted to maximize the clinched joint strength and to obtain high-quality connection. ABAQUS/ Explicit was used for simulating the process. The optimization procedure depended on the minimization of the cost function whereas the response surface method and the sequential quadratic program were used. The data obtained from the study showed that the strength of the clinched joint was strongly affected by the tool shape as seen in Fig. 23. Thus, the optimization procedure is highly needed for the tool design.

Another study performed by Oudjene et al. [45] used the design of experiments based on the Taguchi method to optimize the clinching process parameters to obtain the higher strength possible and the least number of experiments. At the same time, finite element analysis was used to simulate the combination of different parameters of the clinched process tools. The numerical simulation was executed using ABAQUS dynamic explicit with CAX4R axisymmetric element. It was found that the upper neck thickness, the clinch undercut length, and the maximum force required for the sheet pullout constituted the major factors affecting the joint quality. Figure 24 shows an example of the results obtained for one of the parameters affecting the process.

One more study was conducted by Oudjene et al. [46] where the focus was on using a new optimization procedure for the shape of the clinching tools with the use of the response surface methodology by the moving least square approach and the design of experiment procedure. Again, ABAQUS was utilized to simulate the forming of the clinching process of Al5754 alloy with 0.5 thicknesses. In addition, the friction coefficient was assumed to be 0.1 between the lower sheet and the tools and 0.35 between the two alloy plates. The developed optimization procedure led to the improvement of the joints' resistance to tensile loading through the design of optimal geometries of both the punch and the die.

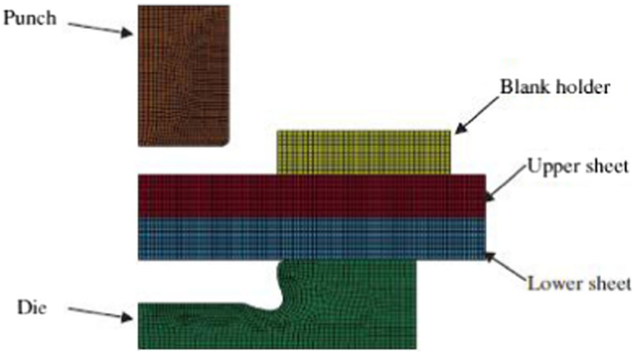


Fig. 19 2D axisymmetric model using LS-DYNA software showing the main components of the clinching process [27]

Roux et al. [47] employed the Kriging metamodel with ductile damage to obtain the optimal clinching joining strength. FE software Forge2009 was used with the 2D-axisymmetric model for the evaluation of the tensile vertical loading and the 3D model for the evaluation of the shear strength of the joint. The results of the simulation showed the strong effect of both the punch radius and die groove on the strength and quality of the joint. However, the radius of the punch corner did not affect the clinching forming process compared to the other parameters as shown in Fig. 25. The ductile damage was induced in the simulation study only, and it needs some experimental investigations. Zhao et al. [48] studied the ductile fracture of the clinched joints by experiments and simulations using a modified Rousselier damage model. The results showed that the Lode parameters in the damage model were able to capture the failure behavior and the evolution process during the clinching process.

A new study concerning the clinching joint simulation and the reshaping of the clinched point was investigated numerically using DEFORM-2D by Wen et al. [49]. The conventional clinching process and the reshaping approach were considered to be elastic–plastic large deformation processes. An axisymmetric FE model was developed with the assumption that the clinching process tools are rigid during the numerical calculations. Similar to most of the other studies, the friction coefficient was approximated to be constant and expressed by Coulomb law. Moreover, a similar optimization procedure to that used in [45] was carried out in this study. The outcome of the simulation and the experiments showed that the strength of the reshaped joint is higher than that of the normal clinched

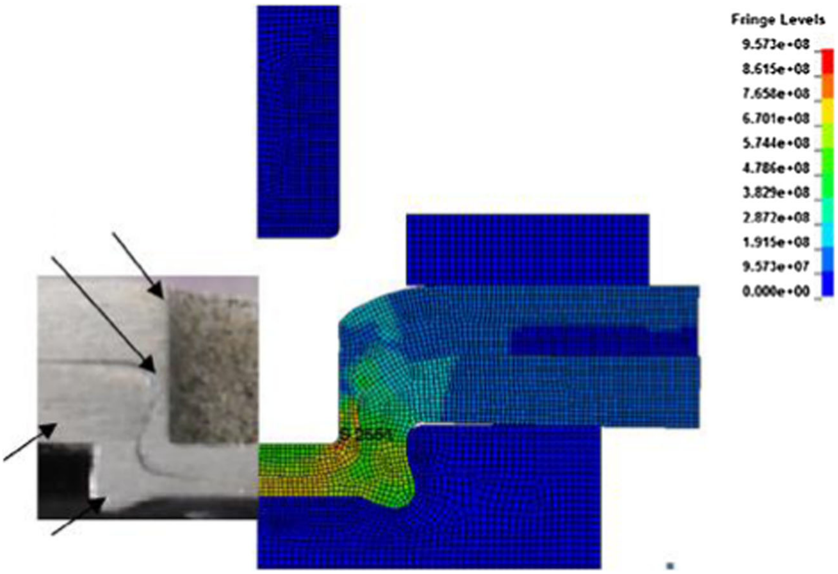


Fig. 20 Numerical and experimental results of a clinched joint [27]

joint with the advantage of less joint height which is preferable and needed in some applications.

Abe et al. [50, 51] investigated the clinching joining of two dissimilar materials numerically and experimentally. The results highlighted the importance of the placement of the two sheets on the joinability of the two materials. Rearrangement of the sheets could lead to different defects, such as cracks in the lower sheet as well as fracture in the upper high-strength sheet, as illustrated in Fig. 26. These problems stressed the need for a geometrical optimization of the tools to eliminate the cause and effects of the sheets' arrangement.

Another parametric and numerical investigation was carried out by Lee et al. [52] about joining dissimilar materials using clinching. DEFORM-2D was utilized to simulate the joining of aluminum alloy Al5052 with DP780 high-strength steel sheets. The friction coefficient was considered constant between the two sheets with a value of 0.35 and 0.2 between the sheet and the tools. As presented in many studies, the interlock length and the upper sheet neck thickness after forming were considered as the main parameters for evaluating the strength and quality of the joint. This study illustrated the effect of the distance between the punch and the blank holder, the die groove, the die depth, and the die radius on the clinch joinability. It was determined that the die radius was the most important factor affecting the joint forming. In addition, cracks occurred in the lower sheet due to the increase in the die depth at the maximum punch stroke.

4 Critical literature analysis

The research and progress in FEA of clinching joints are critically reviewed, and current trends in the application of FEA are mentioned. However, there are still a number of areas that have yet to be investigated using FEM. These issues of

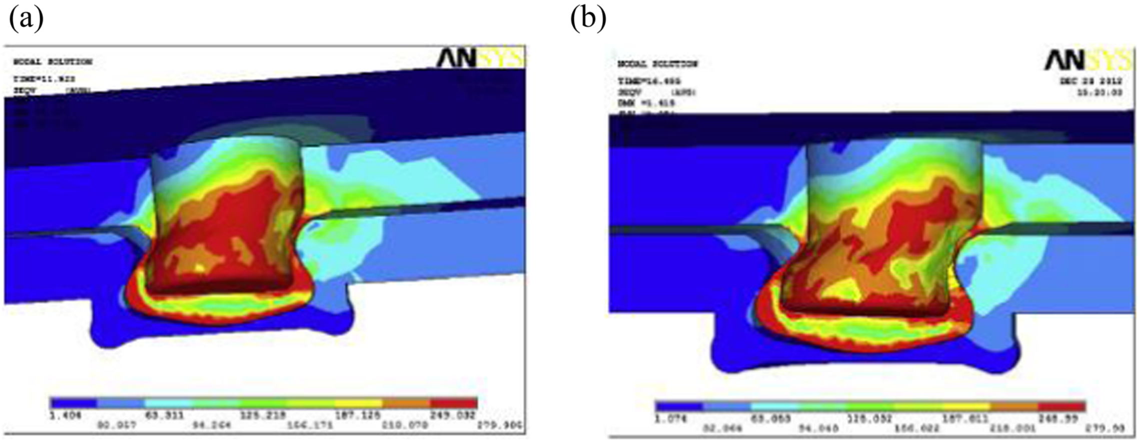


Fig. 21 Simulation results of tensile strength test for 3D model. **a** Stress contour map with deformation 0.7 mm. **b** Stress contour map with deformation value 0.98 mm [27]

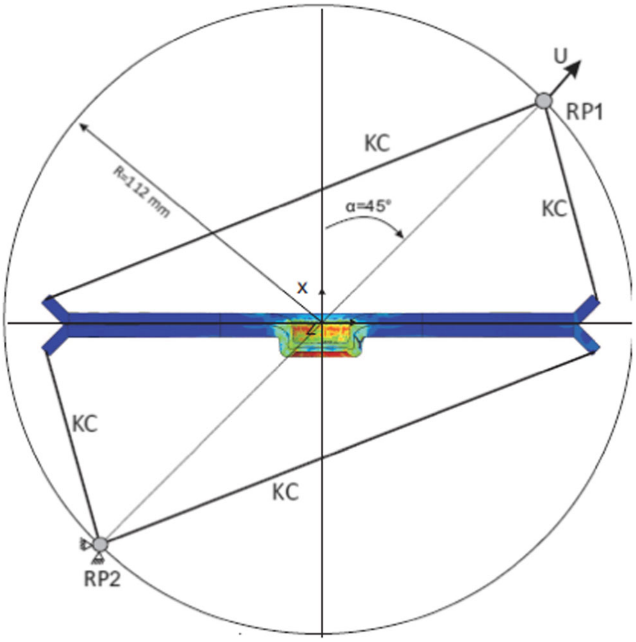


Fig. 22 FE model with the Arcan test [43]

mergers which have not yet been sufficiently explained using FEM but involve clinching technology are described in this section.

4.1 C-frame clinching machines

There are limited studies regarding the usage of FEM to obtain the optimal design of the C-frame machines. Markowski et al. [53] used the FEM to analyze different geometries of the C-frame clinching machines. ABAQUS commercial software was used in order to analyze the C-frame material straining and the mass reduction. Ten-node tetragonal elements (C3D10) were used and designed in the library of the software, where the boundary conditions were applied with the maximum joining force as illustrated in Fig. 27. The results showed that to achieve a low possible weight and frame rigidity, it is important to design the body frame. The frame can have an opening to reduce the weight; however, the opening location and dimensions are considered as very important design factors. The FEM output of the rectangular frame with opening showed that there is a relation between the opening area and the forming force.

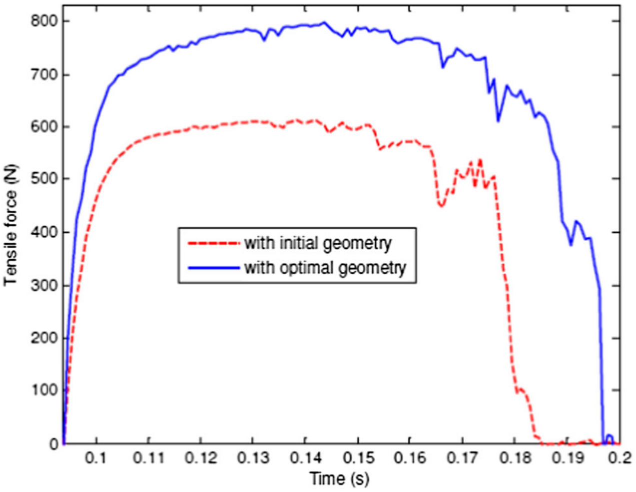


Fig. 23 Tensile force versus the time for initial shape of the clinching tools and the optimized geometry [44]

In addition, the model with circular openings (Fig. 28a) indicated that the deflection value changed with the direction toward the side of the force direction which gives the highest mass reduction whereas the opening through all the surface of the frame (Fig. 28b) resulted in the minimum displacement with high-mass reduction.

4.2 Effect of aging on the strength of clinched joints

The effect of aging on the strength of the clinched galvanized SAE1004 steel to aluminum AA6611 joint was investigated experimentally and analytically by Geo et al. [54]. The results showed that aged aluminum had a minor effect on the clinchability but affected the strength of the clinching joints by strengthening the aluminum AA6111-T4 due to the developed residual stress during the joint forming. However, there was a decreased interlock length with an increased thickness of the clinched joint. In order to estimate the strength of the mechanical clinching of steel to aluminum, an analytical model was developed. The output indicated that the aged aluminum needed large loads to create the interlock between the two sheets.

4.3 Clinch sheet metal riveting joint

Another experimental research was carried out by Mucha et al. [55] without using the FEM. The study analyzed the forming and strength of clinch riveting methods which need additional material to create the connections between the different metal sheets. The results showed that when applying the rivet to connect the two metals sheets, the lock size was increased by 75 % compared to the conventional clinching methods while the required force for obtaining the rivet clinched joint was dramatically increased due to the rivet material type and strain.

4.4 Extensible die clinched joints in titanium sheet materials

Recently, a tensile-shear testing was introduced to determine the mechanical properties of the extensible die clinched joints using titanium sheets [56]. The results showed that the bottleneck of the titanium clinched joint was the failure in the neck. In addition, the relocation of the titanium sheets (upper, lower sheet positions) affected the values of the load-bearing

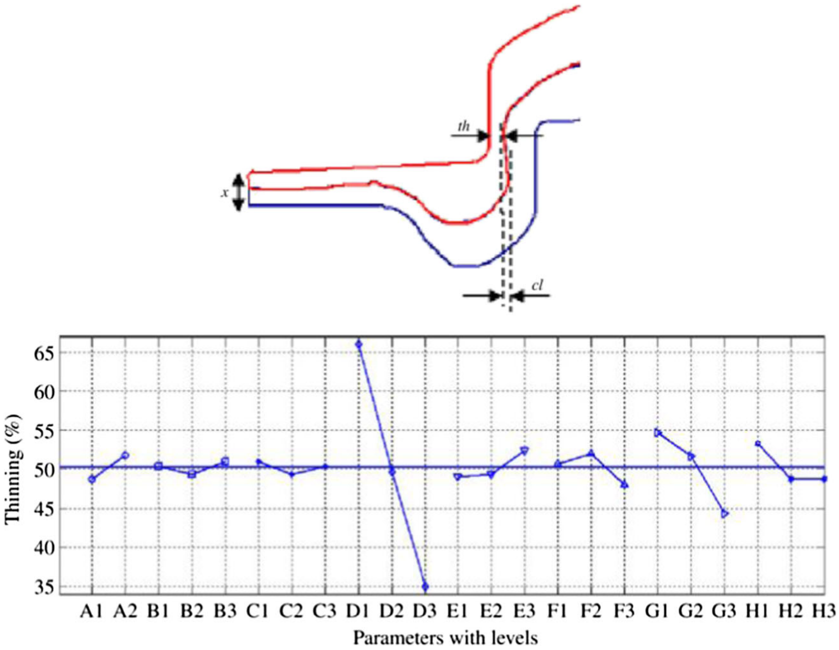
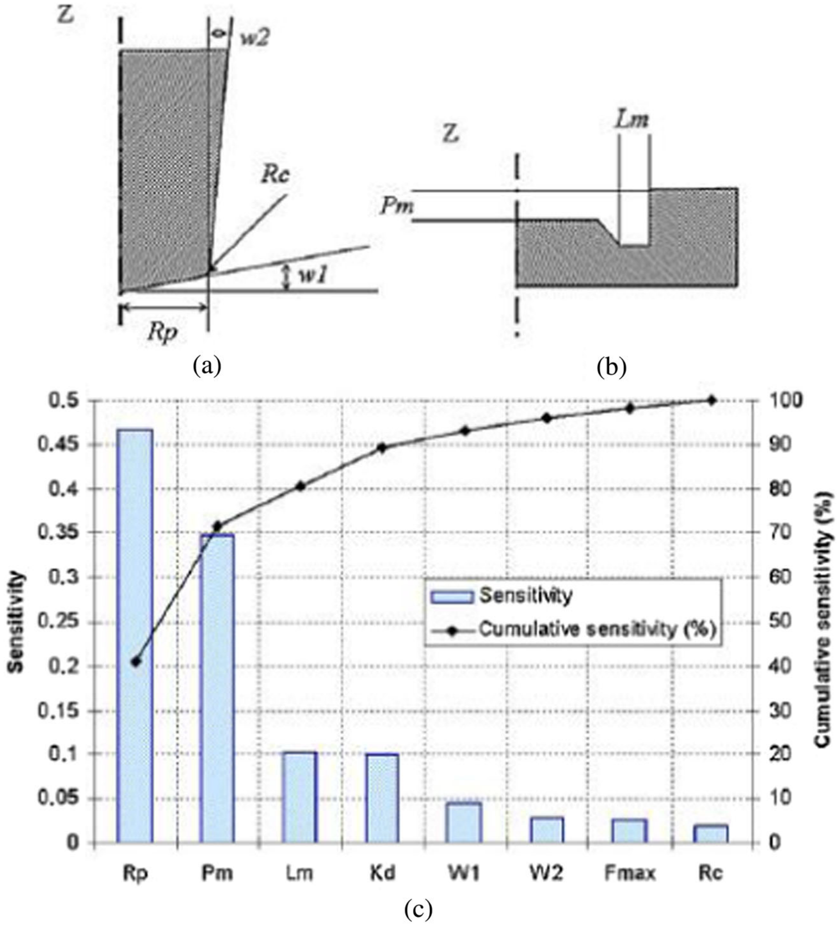


Fig. 24 The average parameters effect related to the chosen level in the design experiments on the neck thickness (*th*) [45]

capacity and the energy absorption of the clinched joint. When the titanium sheet was located at the punch side, the load-bearing capacity and energy absorption give higher values compared to the titanium sheet die position. Joining of



(a) (b)

(c)

Fig. 25 2D-axisymmetric view of the **a** punch and **b** die. **c** The sensitivity study for the clinching process parameters [47]

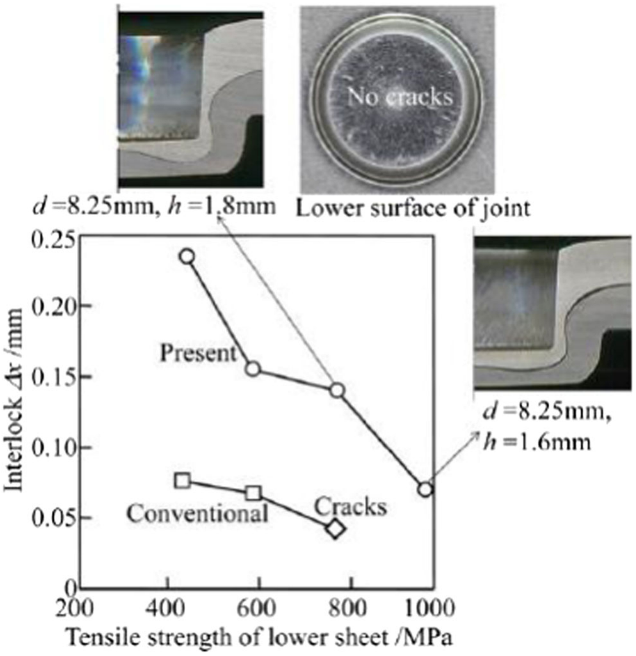


Fig. 26 New dimensions of the die diameter and height with its relation to the interlock length and cracks appearance in the lower sheet with high strength [51]

titanium TA1 with copper alloy H62 and titanium TA1 with aluminum AA5052 can be achieved by using the extensible die clinch methods.

4.5 Joining materials used in car body production by clinching

Various types of materials must be joined using the same clinching tools in car body assembly. While joining sheet metals of various strength and plasticity using clinching, the sheet arrangement in relation to the die is very important. Mucha et al. [57] presented an experimental study into joining materials DX51 and DP600 by clinching. Analyses were performed for four sheet metal arrangement combinations in relation to the die and punch, and the resulting joints were shear tested. They found that joining DX51 sheets with DP600 sheets is possible in each arrangement. However, the best results of material clinching were achieved for DP600/DX51 arrangement. Increasing the joint diameter from 5 to 8 mm resulted in increased strength. Higher forming force also increased the clinching joint strength.

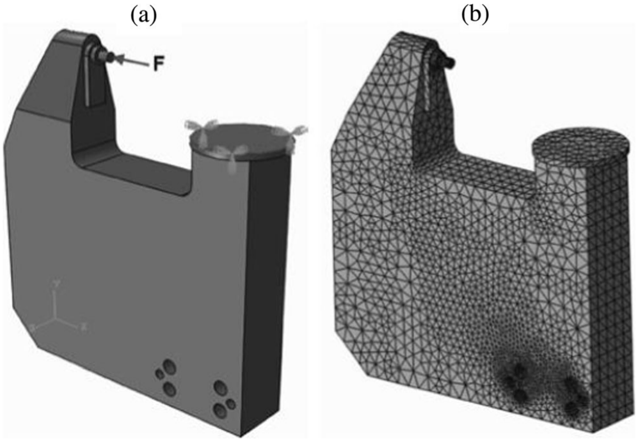


Fig. 27 C-frame-based views; **a** solid model with boundary conditions and load, **b** finite element mesh [53]

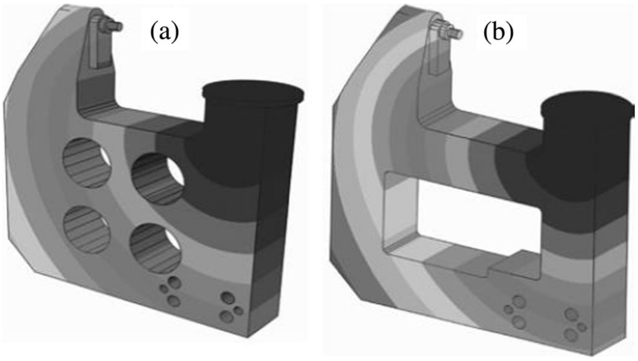


Fig. 28 Distribution of resulting displacement of C-frame for various material recess geometries [53]

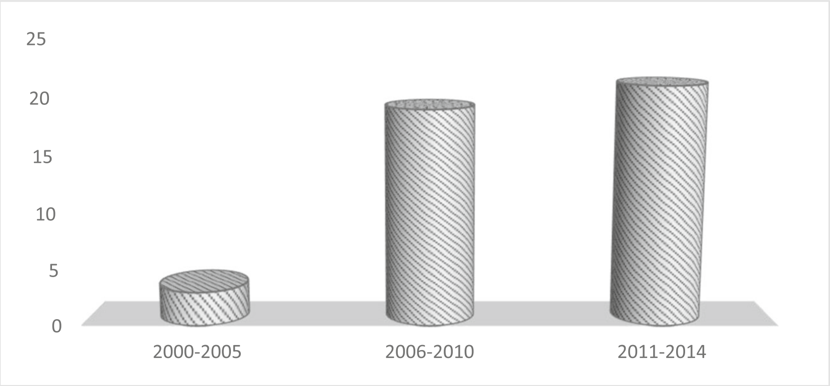
4.6 Analysis of the clinched joint mechanism

Various punch diameter and bottom thickness parameters of the clinched joint were investigated by analyzing the joint strength. Mucha et al. [58] used two types of mechanical testing to obtain the maximum joint strength of the lap joints: T-shape and H-shape tests. The results indicated that increasing the joint strength can be obtained by decreasing the bottom thickness which leads to an increase of the forming force and the energy consumption. The increase in the forming force caused a reduction in the zinc layer of the galvanized sheet due to the flow of the material into the die cavity and groove. This can cause corroded areas in the future. Using the mechanical shear testing for various samples with different bottom thickness and load angle values showed different failures and separation modes.

4.7 Clinched joints realized with different dies

Lambiase and Di Ilio [59] conducted an experimental investigation to assess the main differences among clinched joints produced with different die configurations, including an extensible die and three different fixed dies. The samples were joined with different forming forces and were analyzed by means of different mechanical tests, including lap shear tests, with one and two joints, and peeling tests. The results showed that the employment of extensible dies allows producing large interlocks which result in an increase in strength and absorbed energy of joints during peeling tests. However, the joints produced with the fixed dies are characterized by the highest

Fig. 29 Evolution of clinching simulation research in recent years



strength and absorbed energy when loaded in the lap shear test with one joint.

4.8 Effect of pre-straining on the strength of clinched joints

The pre-strain from the pressing or stamping prior to mechanical clinching had a large effect on the quality of the joint. Jian et al. [60] conducted a study where the clinching process parameters such as the interlock length, neck thickness, and bottom thickness were measured to investigate the pre-straining effect on the clinched aluminum–steel sheets by static strength measurements. The results showed that pre-straining induces ductile damage in clinched regime and degrades joint quality. Indeed, the pre-straining of aluminum AA6111-T4 by a percentage of 5 % caused the strength of the joint to be decreased by 20 %. It was also found that the bottom thickness barely detects the effect of pre-strained aluminum on clinching and that the electrical resistance of clinching joint is sensitive to ductile damage in joints. Therefore, they proposed a method of monitoring the variation of electrical resistance of the joints during the clinching process in order to differentiate the difference of the damage between the as-received and pre-strained clinched joints.

5 Summary

The mechanical behavior of clinched joints and the recent developments in clinching technology are reviewed. During recent years, researches about the mechanical clinching technique for joining dissimilar materials without the need of additional material dramatically increased. Figure 29 illustrates the high rise in the simulation researches of clinching methods during the last 10 years. Nowadays, simulation of the clinching process is still a hot research topic that aims to develop accurate and efficient models of the clinched joint especially for dissimilar materials. In addition, the mechanical behavior of the joints is affected by the different process parameters. This FEA literature review showed that there is an extremely big gap between scientific research and the development of the process in the industrial application. In addition, it was found that there was no systematic review of both the numerical and experimental investigations in order to critically highlight the remaining research venues to improve knowledge of the clinching process. Moreover, the introduction of damage failure and its effect on the process needs further investigations with different methods and models. There were no studies with a full detailed optimization of all the process and geometrical parameters that affect the forming of the joint.

Another shortcoming from the published work during the last 10 years is the lack of generic algorithm and simulation steps of the different variants of the clinching process. Furthermore, there were no studies dealing with testing the joints using nondestructive examination methods. These important avenues for future work related to the simulation, experimental, and joint testing need to be explored in order to achieve high-quality and high-strength joints of dissimilar materials. Only then will clinching be able to gain more ground in replacing the old and conventional joining methods.

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