ACTA METALLURGICA SLOVACA
2022, VOL. 28, NO. 4, 219-223

RESEARCH PAPER

NUMERICAL AND EXPERIMENTAL STUDIES ON CLINCH-BONDED HYBRID JOINING OF STEEL SHEET DX53D+Z

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Received: 21.11.2022
Accepted: 05.12.2022

ABSTRACT

The automotive industry is characterized by the fact that it uses an entire range of materials. These are materials with different mechanical properties, thicknesses, and even different combinations. A variety of joining methods, such as clinching, is used to join this range of materials. However, sometimes it is necessary to combine several methods of joining materials. The paper deals with the evaluation of the properties of joints, which are created by a combination of mechanical joining and adhesive bonding. Two types of adhesives were used: adhesive based on epoxy resin and adhesive based on acrylate polymers. Double-sided hot-dip galvanized steel sheets DX53D+Z with a thickness of 0.8 mm were used to join with this combination of joining techniques. Numerical simulation tools were used to assess the joinability of materials. The simulation results were verified by the results from the experiments of real test samples. Samples joined by the clinching method combined with epoxy resin adhesives achieved higher load-bearing values and no cracks or any other type of failures were observed in these joints.

Keywords: clinch-bonding; FEM simulation; tensile test; metallography

INTRODUCTION

Nowadays, alternative methods of joining materials are increasingly used in the automotive industry. Car producers are trying to either partially or completely replace the most used method of joining car body sheets - resistance spot welding (RSW). The reasons for replacing RSW result from the need to join various ferrous and non-ferrous materials (mainly based on aluminum alloys), their different thicknesses and qualities, and their mutual combinations as well [1-5]. It is also necessary to consider high thermal conductivity, the natural surface oxide layer, and others which result in welding problems. It is relatively difficult to weld hot-dip galvanized sheets. During spot resistance welding, zinc diffuses into the CuCr welding electrodes, which causes the formation of a brass layer on the contact surfaces of the welding electrodes. This brass layer significantly affects the transient resistance between the electrodes and the welded materials. Ultimately, this leads to wear of the electrodes and to a decrease in the quality of the weld joints. In addition, spark and smoke produced during the welding process is not environmentally friendly. The use of different types of materials and various thicknesses results from the requirement to reduce the weight of cars, with the aim of reducing fuel consumption and thereby reducing the emissions in the air [6-8].

Mechanical joining methods are considered as alternative methods. There are variety of mechanical joining methods that use different processes, such as thread fastening, riveting, and clinching. Some automotive producers also use clinch-riveting, self-piercing riveting, flow-drill screwing, friction-element welding, roller hemming, grip punch-riveting [9-11]. Mechanical methods of joining have the following general advantages over conventional ones [12, 13]:

- there is no thermal influence on the joined materials, which means that there is no change in the structures of the joined materials,
- it is possible to join a wide range of metallic and non-metallic materials and their various combinations, including the combination of different thicknesses of the joined materials,
- checking the quality of the joints is simple and fast, in practice the thickness measurement of the bottom of the joint is used,
- no pre-treatment of the surfaces of the materials to be joined is necessary,
- materials whose surface is coated or treated for corrosion resistance are connected without damage to the surface layer,
- mechanical joining methods are also interesting from an environmental point of view, because harmful gases or other types of pollution are not produced during joining,
- connection processes are highly reliable and fast, the connection speed is around 1 second by default.

The joints are the most critical parts of the structure and their use in the structure is unavoidable, obviously, there should be more attention on the joining methods. Clinching with rigid die is one of methods of mechanical joining for materials with various properties and thicknesses. Clinching is an economic and environmental fast joining process, which purely relies on mechanical local cold forming without additional joining elements [14, 15]. Compared to resistance spot welding, the advantages of clinching joining are its low cost, joining speed, environmental friendliness, joint reproducibility, and tool (punch and die) durability. During the clinching process, sheets are joined together by forming an interlock by using a punch and a specially formed die. Clinching is a complex mechanical joining influenced by

the parameters of the process itself and the parameters of the tool geometry [16,17].
The load-bearing capacity of the clinched joint is determined by the formed interlock between joined materials, but the values of the load-bearing capacity are not so high in comparison with other joining methods (especially resistance spot welding. Increase of load-bearing capacity of the clinch joints can be done by additional bonding of joined components. This solution appears to be very advantageous - the use of two different joining techniques brings a combination of their advantages and at the same time eliminates their shortcomings The creation of a hybrid joining method clinch-bonding by a combination of mechanical joining - clinching and adhesive bonding offers new application possibilities: increases the load-bearing capacity of the joints, ensures the waterproofness of the joints, improves the vibration suppression feature or serves as a physical isolation barrier for corrosion protection [18-20].
Research in the field of clinch-bonding has mainly focused on the use of epoxide resin adhesives and acrylic low-odour adhesive in combination with clinching. The thickness of the used adhesive varied from 0.1 to 0.2 mm. The advantage of the clinch-bonding is that it allows the use of not only fluid or pasty adhesives, but also of adhesive foils and bands. Research has shown that, compared to pure clinching, in hybrid fastening, an additional strengthening mechanism of the joint is created by the adhesive at the place of clinching and also in the overlap area of the hybrid joint. This significantly increases the load-bearing capacity of the joints and its energy absorption in case of failure [20-24].
The paper deals with the evaluation of the joinability of samples with DX53D+Z steel sheets created by a combination of mechanical joining and adhesive bonding. For the experiments, adhesive based on epoxy resin and adhesive based on acrylate polymers were used. Numerical simulation tools were used to predict the joining of the examined combination of joining techniques. The results of numerical simulation were consequently verified by the results from the experiments.

MATERIAL AND METHODS

Joined material

Double-sided hot-dip galvanized steel sheet DX53D+Z of 0.8 mm thickness was used for joining by the clinch-bonding method. This type of material is from drawing grades steels, and it is suitable for cold forming and deep-drawing process. They are used to produce automobile parts, in building industry and for production of profiles, corrugated sheets, roof coverings and engineering. The basic mechanical properties and chemical composition are shown in **Table 1** and **Table 2**.

Table 1 Basic mechanical properties of DX53D+Z

Material	$R_{p0.2}$ [MPa]	R_m [MPa]	A_{80} [%]
DX53D+Z	163	340	28

Table 2 Chemical composition (in [%] of wt) of DX53D+Z

C	Si	Mn	P	S	Si	Al	V	Ti
0.0 35	0.0 19	0.1 76	0.0 06	0.0 02	0.0 19	0.0 50	0.0 02	0.0 02

Adhesives

Two different types of adhesives were used in the experiments:
1. adhesive based on 2-component epoxy resin (with the layer thickness of 0.6 mm)
2. adhesive based on 2-component acrylate polymers (with the layer thickness of 1.6 mm)

<u>Technical data of 2-compononet epoxy resin:</u>

Component A	Epoxy Resin
Component B	Amine
Mixing ratio A:B	1:1
Curing times initial strength	approx.. 4 h at 23°C
Shear strength – final strength	approx.. 2 d at 23°C or 30 min. at 100°C
Shear strength	18 ÷ 22 MPa
E-modulus	1,500 MPa
Optimal layer thickness	0.2 ÷ 1 mm

The adhesive based on 2-component epoxy resin is characterized by very good adhesion properties in combination with metals, aluminum alloys, galvanized steels and galvanically coated panels. The primary area of use is the automotive industry, or related industries requiring high strength and anti-corrosion protection.

<u>Technical data of 2-component acrylate polymer:</u>

Component A	ADP Acrylic
Component B	2K Acrylic
Mixing ratio A:B	10:1
Curing handling time	approx.. 9 min. at 23°C
Final curing time	> 15 min. at 23°C
Shear strength	10 MPa
E-modulus	250 MPa
Optimal layer thickness	0.5 ÷ 3 mm

The second type of glue was a fast-curing, flexible, structural, 2-component adhesive based on ADP (Acrylic Double Performance) polymer technology. It is characterized by very good adhesive properties in combination with metal materials. Unlike epoxy adhesives, a big advantage is the increase in joint strength within a few minutes, which ensures a quick possibility of handling the joined materials. The formation of the joint takes place by radical polymerization of the adhesive components representing acrylate polymers, which generate residual heat during the reaction.
The thickness of the investigated adhesive layers was chosen approximately in the middle values of the optimal recommended thicknesses. In this case, it was about hybrid joints where it is very important to ensure water resistance of the joints and to improve the function of suppressing vibrations.

Numerical simulation of clinch-bonding process

The simulation software Simufact Forming was used to predict the clinch-bonding process when joining two steel sheets of DX53D with an adhesive layer (**Fig. 1**). As part of the optimization of the hybrid process of joining, different values of the punch stroke were observed. The task was simplified on a 2D model because the tools (punch, die, and the blank holder) and the joint itself are axially symmetrical. For this reason, the anisotropy of the joined materials will not be considered in the calculation. The significant parameters that had to be defined before the process of the simulation include the holding force, the friction coefficient, and the distance of the punch stroke were defined. The contacts between the joined materials as well as the contacts between the tools and joined materials were described as frictional contacts. The friction coefficient of 0.12 between tools and sheets and friction coefficient of 0.2 at the sheet metal - adhesive layer interface were determined. The last boundary condition is a holder force of 100 N that operates on the body of the sheet holder to fix the joined materials during the simulation of the process of clinch-bonding. When the prescribed stroke distance has been reached, the punch performs a backward stroke movement to the starting position. The specially shaped punch, die and sheet holder were modelled as perfectly stiff - non-deformable bodies. The joined sheets in combination with the adhesive layer were modelled as deformable bodies.

DOI: 10.36547/ams.28.4.1657

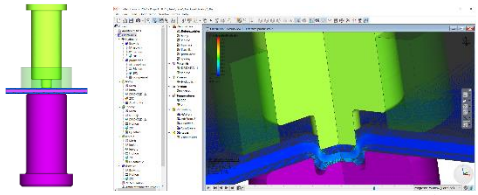


Fig. 1 Setting up the simulation task in the simulation software environment

Clinch-bonding process

A hybrid joint involving adhesive bonding and mechanical joining is produced based on three specific methods [25]:

1. Fastening method - the connection of materials takes place by applying a adhesive layer, then a mechanical joining takes place immediately afterwards. The mechanical joint is applied before curing of the adhesive layer.
2. Injection method - first a purely mechanical joint is created, then the resulting gap between the materials is filled with adhesive using injection. The capillary effect ensures the spread of the adhesive over the entire surface between the materials, where it finally hardens.
3. Step-by-step method – a adhesive joining is the first applied method and the subsequent mechanical joining is applied only after the final hardening of the adhesive layer.

In the experiment, the step-by-step method of hybrid joint was applied. The creation of hybrid joints consisted of a combination of clinching and adhesive bonding. The principle of creating a joint consists in a specifically determined technological procedure:

- Application of adhesive layer with the necessary steps consisted of a procedure such as polishing the sheets' surfaces with abrasive paper and then degreasing the surfaces using ethanol.
- Curing of the adhesive layer to the final strength.
- Application of the mechanical joining method – clinching.

The hybrid joints were created after the final hardening of both types of used adhesive layers and the subsequent application of the clinching method (**Fig. 2**). The essence of this procedure consists in the creation of an adhesive layer that joined the individual materials. After application of mechanical joining, the adhesive layer behaves as a third intermediate layer. This creates a connection whose properties are affected by the location of the adhesive layer between the sheet metal layers. The advantage of this design is the absence of a part of the glue leaking when the mechanical joint is applied immediately after applying the adhesive layer.

Fig. 2 Methodology of hybrid sample preparation - curing of adhesive layer before clinching

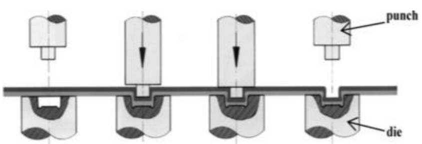


Fig. 3 Clinching process [26]

The principle of the clinching method is well known (**Fig. 3**) and was described in [26]. All the clinching processes were performed by pressing the punch at a constant speed of 8 mm/s and stroke of 3.0 mm.

Tensile test

The tensile tests were executed under displacement control conditions on clinched-bonded samples in order to characterize the static behavior of the joints and to estimate the ultimate tensile strength. The maximum shearing load was the most significant value obtained from the ''load-displacement'' curves, which were recorded during the tensile test. Samples joined only by the clinching method were prepared for the tensile test as well. They were used to compare the load-bearing capacity with clinch-bonded ones.
The samples with dimensions of 30 x 90 mm and 30 mm lapping were used for the experiments. The test was carried out on the metal strength testing machine TIRAtest 2300 produced by VEB TIW Rauenstein, with the loading speed of 8 mm/min.

Metallographic observation

The clinch-bonded joints were also evaluated by metallographic observation in terms of the occurrence of defects in the joints such as cracks, failures, or insufficient formation of interlocking in the joint. The cross-section samples of the clinch-bonded joints were compared with the results of the numerical simulation as well.
The preparation of the sample for metallographic observation consisted of creating a cross-section one, its grinding, polishing and etching. Metallographic observation was realized on digital light optical microscopes KEYENCE VHX-5000.

RESULTS AND DISCUSSION

Clinch-bonding simulation

During the process of clinching, the critical zone is located on the punch side directly to the top sheet metal. The maximum plastic deformation is situated in the top sheet at the area where it is excessively thinned - the area of the neck of the joint.

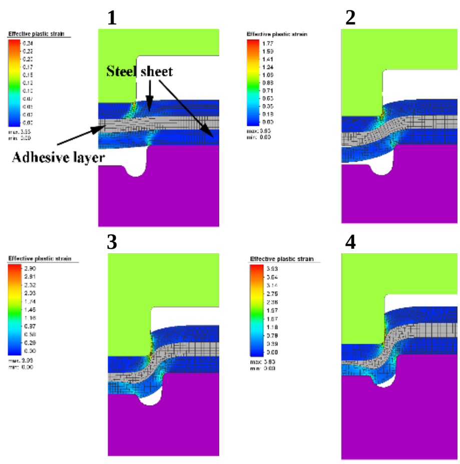


Fig. 4 Clinch-bonding simulation: clinching and epoxy adhesive

Fig. 4 shows results of numerical simulation of hybrid joint – clinching and epoxy adhesive divided into four phases. The numerical simulation showed that the clinch-bonded joint created with this type of epoxy adhesive can be formed, but its strength will depend on the adhered part of the joint. Mechanical interlocking, typical for a clinching joint, will not occur.

DOI: 10.36547/ams.28.4.1657

Fig. 5 shows results of numerical simulation of hybrid joint – clinching and acrylate polymer adhesive. The numerical simulation pointed out that in the clinch-bonded joint with this polymer adhesive and with the investigated thickness, the failure in top sheet will occur even during the joining process. We can assume that the clinch-bonded joint will be functional due to the adhered parts, but the clinching phase and especially the crack in the joint interlocking area is an undesirable element. This would be unacceptable from the point of view of evaluating the quality properties of the joint.

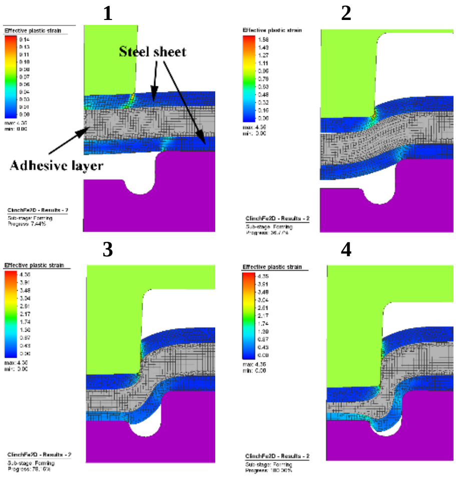


Fig. 5 Clinch-bonding simulation: clinching and acrylate polymer adhesive

Load-displacement curves

The load-displacement curves obtained from tensile test are shown in **Fig. 6**. The form of the curves indicates the behavior of the joints under load - the maximum shearing load and capacity for deformation. In this case, the maximum shearing load

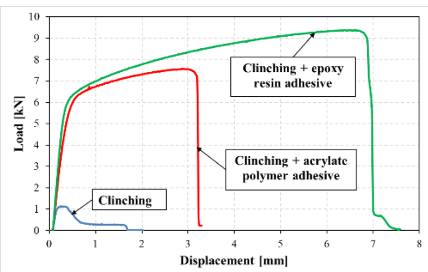


Fig. 6 Load-displacement curves of clinched joint, clinch-bonded joint with acrylate polymer adhesive and clinch- bonded joint with epoxy adhesive

value was measured on clinch-bonded sample with epoxy adhesive (around 9.3 kN) with the corresponding displacement about 6.8 mm. The clinch-bonded samples with acrylate polymer adhesive reached the maximum shearing load value around 7.5 kN with the corresponding displacement about 3.2 mm. The lowest maximum shearing load values were measured on the pure clinched joints (around 1.1 kN) with the corresponding displacement about 0.2 mm. Both adhesive causes the increase of the clinch joint load-bearing capacity and energy absorption.

Cross-section metallographic observation

The macrostructure of the pure clinching joint with the microstructure of typical interlocking area is shown in **Fig. 7**. Well-formed parts of bottom of clinched joints with typical shape of groove die are visible as well. No defects such as cracks, violations, or insufficient interlocking of the joints can be seen in the joint.

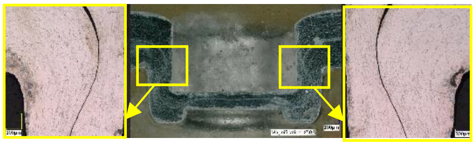


Fig. 7 Cross-section of pure clinching joint with marked area of interlocking

The structure of clinch-bonded sample with epoxy resin adhesive is visible in **Fig. 8**. From the point of view of the shape of the joint, it can be stated that the joint is sufficiently formed, with a typical shape of groove die. The adhesive layer is significantly thinned in the area of interlocking. Due to the thickness of the adhesive layer, there is no typical mechanical interlocking defined for a clinching joint. A double interlock was created, which can be observed when clinching three sheets. No inner defects such as micro-voids or micro-fractures zones in the clinched joints occurred.

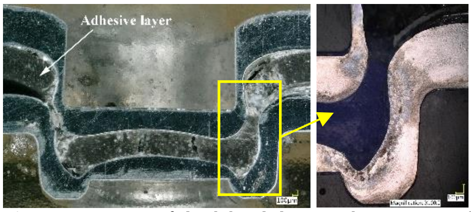


Fig. 8 Cross-section of clinch-bonded joint with epoxy resin adhesive; marked area of interlocking

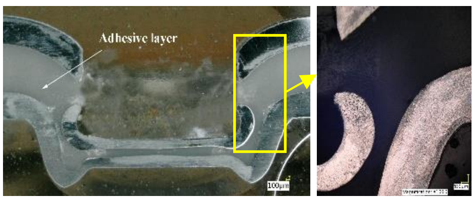


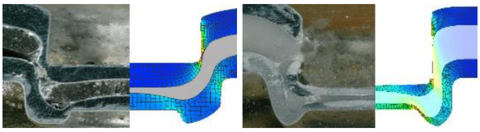
Fig. 9 Cross-section of clinch-bonded joint with acrylate polymer adhesive; marked area with a failure in the interlocking

The clinch-bonded sample with acrylate polymer adhesive failed during clinching process. The failure occurred in the interlocking area of the clinch-bonded joint. There was a separation of a part of the top sheet in the place under the punch and this part was locked in the joint – **Fig. 9**. The formation of this failure during clinching process was also predicted by numerical simulation (Fig. 5). Due to the thickness of the acrylate polymer adhesive used in the clinch-bonded joint, plasticity reserves were exhausted in the top sheet and this led to the appearance of a crack even during joining.

Fig. 10 shows a comparison of the cross-sections view between the created clinched joint (left side) and the joint resulting from the simulation (right). Based on the results after simulation, we can deduce that real clinched joints can be compared with values after simulation, such as the thickness of individual sheets or the

DOI: 10.36547/ams.28.4.1657

interlocking between the joined sheets (called the "S" shape of the sheets) can be compared. Based on the visual comparison of the results, it is possible to state with certain tolerance that the simulation results correspond to the result of the actual joining process.



a) b)

Fig. 10 Cross-section of clinch-bonded joints: a) with epoxy resin adhesive, b) with acrylate polymer adhesive

CONCLUSIONS

In this work, the joinability of samples with DX53D+Z steel sheets created by a combination of clinching and adhesive bonding was investigated. Two types of adhesives - acrylate polymer adhesive and epoxy resin adhesive were used. Both investigated adhesives significantly increased the load-bearing capacity of clinched joints. The main conclusions are as follows:

In clinch-bonded joints with acrylate polymer adhesive, cracks appeared in the interlocking area already during the joining process. Although the load-bearing capacity of these joints (7080 on average) was higher compared to the pure clinched joint (1045 on average), such joints cannot be acceptable for practical use. The importance of using clinching as a second joining method is lost, and also a crack in the top of the sheet could lead to degradation processes that negatively affect the strength of the joint.

In clinch-bonded joints with epoxy resin adhesive, cracks did not appear during the joining process in the interlocking area. The load-bearing capacity of these joints was the highest among the measured samples (9080 on average). The examined thickness of the adhesive was not compressed (deformed) enough in the joining process to create a classic mechanical interlocking area as in a clinching joint. On the metallographic cross-section sample, this joint appears as a joint consisting of three sheets, where two areas of interlocking should be defined.

If it is necessary to combine clinching with glue with a greater thickness of the glued layer, it is more appropriate to use glue based on epoxy resin.

Acknowledgements: Authors are grateful for the support of experimental works by projects APVV-17-0381, APVV-21-0418 and VEGA 1/0259/19.

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