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ORIGINAL ARTICLE

Durability of hybrid clinch-bonded steel/aluminum joints in salt spray environment

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Abstract In this work, hybrid aluminum alloy/steel joints by combining clinching and bonding processes were realized. Furthermore, we investigated how the presence of an adhesive interlayer can influence the performance of hybrid joints when exposed in salt spray environment up to 15 weeks of ageing. The durability of steel/aluminum joints is a well-known problem, in particular for steel-reinforced aluminum frames, in aggressive environmental conditions. The aluminum alloy/steel joints were made by interposing an adhesive layer (modified silane (MS) polymer) and clinching before the polymerization has taken place. A proper design of experiment has been carried out, followed by the ANOVA of the results. The experimental results of long-term ageing tests (ASTM B 117) evidenced that the corrosion degradation phenomena influenced significantly the mechanical performance of the hybrid joints. By comparison with the pure mechanical clinching joints, in the same configurations studied in a previous work, the shear load trends are similar. The presence of the flexible adhesive layer gave a significant advantage on resistance to a corrosive attack but little influences the mechanical strength.

Keywords Clinching · Corrosion · Durability · Salt spray environment test · Single-lap shear test

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1 Introduction

Nowadays in the manufacturing field, the tendency is to choose materials and technologies aimed to functionality, durability, with energy and cost saving. Therefore, the choice to leverage existing technologies, also combining them with each other to design lightweight, innovative, and sustainable products, is becoming more frequent and important.

The trend of multi-material design has led to new challenges in the joint engineering by combining manufacturing techniques too [1, 2]. In joining field, there are different assembly processes, welding (spot, arc, and laser welding), mechanical fastening (bolting, riveting, and clinching), and adhesive bonding. Where thermal joining techniques have reached their limits or are not able to produce high-strength joints or where the assembly without adding major joining elements is required, the clinching process results a good technological solution. Clinching is largely used to join certain parts of an automotive body [3, 4] (e.g., in the rear end of the car, there are clinch points on the floor, the rear apron, and the light holder). In some cases, steel-formed components, made by deep drawing, are joined with aluminum alloy parts.

Clinching is indicated for coupling, similar or dissimilar, pre-coated or galvanized, material sheets, up to a total thickness of 3 mm; i.e., Liu et al. [5] investigated the influence of material property on the mechanical property and failure mode of clinched joints.

This technique realizes interlocking friction joints without affecting the performances or inducing thermal stresses between plates. The mechanical stability of clinched joints is influenced by several factors such as the accurate selection of process parameters or the geometry of assembled materials [6]. The static strength of clinched joints is lower than that of other joints (e.g., made by self-pierce riveting and spot welding), but their fatigue strength is comparable to that of the other joints; i.e., Xu et al. [7] analyzed the technology characteristics of self-piercing riveting with clinching. Nowadays, many researches are looking for appropriate combination of clinching tools to obtain the maximum load under shear test of the clinched joint by studying the process also carrying out appropriate finite element analyses [i.e., 8–19].

Drawbacks of this cold-formed mechanical fastening can be also improved by hybrid joining, involving clinching and adhesion techniques. The introduction of an additional adhesive layer between substrates aims to strengthen simple joining process as clinching. A higher static strength, improved fatigue strength, avoiding of sealing operations, and better corrosion resistance are positive effects that can be achieved by using hybrid joints [20–23]. T. Balawender et al. [24] have dealt with discussion of technological aspects and experimental investigations of clinched lap joints of different metal strips combined with adhesive bonding, which can be applied in different branches of engineering. The application of clinching with adhesive bonding leads to a mechanical performance improvement (in comparison to a simple joint) of quality, rigidity and load capacity, dumping of noise and vibration, pressure tightness, and corrosion protection.

This entails a significant increase of long-term static strength, of force amplitude under fatigue test, and required energy to the rupture of the hybrid joint under static, dynamic, and impact loading. In principle, the choice of the combined mechanical fastening and adhesive joining technologies, which may be used for joining in light constructions, depends mainly on two application criteria. In mechanical fastening combined with adhesive joining, the former is the main joining process; thus, the role of the adhesive is primarily as a sealant, corrosion inhibitor and/or as a damping material. In adhesive joints combined with mechanical joining, the former is the main joining process. The mechanical joining serves as a positioning help and is useful to withstand peeling forces and long-time static forces [25]. Several phenomena can arise during the ageing of such kind of joints, due to galvanic effects, to the presence of stress-induced corrosion cracking, and to the presence of oxide films that depending on the environment pH value can form on the surface of the metals [26–28].

In order to prevent the degradation of metal caused by the corrosion phenomena, Saberi et al. [29] treated the surface with a corrosion protection primer by showing that the CPP-coated clinched joints have a relative lower maximum shear forces than blank joints.

Hybrid adhesive-clinch joints are nowadays more and more used both in automotive [30], where the needing for weight reduction leads to increase the use of aluminum alloys, and in naval field [31], thanks to the possibility to obtain sealed joints also among dissimilar materials. Indeed, the problem of durability of steel/aluminum joints is well known, in particular, for steel-reinforced aluminum frames, mainly in aggressive environment such the marine one. Accelerated corrosion tests or accelerated ageing tests (i.e., salt fog test) are usually carried out to evaluate the durability of the joints in highly aggressive environments.

LeBozec et al. [32] developed a device that allows corrosion-fatigue tests to be performed on joined samples inside a climatic chamber during a cyclic corrosion test and evaluated the influence of simultaneous fatigue loading on corrosion resistance of joined samples, in terms of tensile strength loss, failure mode, and corrosion in the overlap area. They observed that combining adhesive bonding and clinching resulted in better mechanical performance than clinching alone. However, simultaneous fatigue corrosion had a detrimental impact on the fatigue performance of clinched-bonded joints, particularly at the lowest frequency.

Pinger et al. [33] stated that the use of thin film batch-galvanized material leads to high-quality clinch joints. The ductile thin film zinc layer increases the resistance of the clinch joint against corrosion, and the mechanical load-bearing behavior is positively influenced due to a better reproducibility rate. This means an increase of the reliability of clinch joints regarding its durability as well as its mechanical load-bearing capacity.

Calabrese et al. [34–37] performed long-term ageing tests in critical environmental conditions to evaluate the mechanical durability of symmetrical or asymmetrical aluminum alloy/steel SPR joints. The experimental results evidenced that the corrosion degradation phenomena significantly influenced performances and failure mechanisms of the joints. Moroni et al. [38] have shown the influence of thermal cyclic ageing on the performances of hybrid adhesive-mechanical joints, whereas ageing influences slightly the performances of hybrid joints. Although the long-time durability of the clinched joint in a corrosion environment is a known problem, only few works focus the attention on the relationship between joint durability and electrochemical behavior of the metal constituents. Yang Gao et al. [39] have shown the effects of aged aluminum on the strengths of the clinching steel-aluminum joints. The results showed that the ageing of aluminum alloy not affected significantly the clinching ability but influenced the section parameters and strength of the clinching workpieces. This is also due to the internal stress states induced during clinching process.

In our previous works, the degradation of clinched joints [40] and modifications of the failure mechanisms [41] have been studied, evidencing a drastic reduction of mechanical performances in critical environmental condition due to mainly galvanic corrosion phenomena. In this work, we investigated how the presence of the adhesive interlayer could influence the resistance of hybrid aluminum alloy/steel joints exposed in salt spray environment.

Two clinch-adhesive joint configurations have been tested under single-lap shear test at increasing ageing time (salt spray fog test). The results have been compared with those ones obtained without adhesive interlayer [40], evidencing some interesting differences in damage and degradation phenomena.

2 Experimental setup

2.1 Materials

2.1.1 Metal sheets

Aluminum alloy AA6082 sheets, a very tough and durable alloy, commonly applied in aircraft and aerospace applications, and carbon steel A570, used for structural purposes, were used as joining plates. Chemical composition and mechanical properties of the alloys are reported in Table 1. Dimensions of each metal strip are 100 and 25 mm, length and width, respectively. The sheet thicknesses were 1 and 1.5 mm for both alloys.

2.1.2 Adhesive

A modified silane (MS) polymer-based adhesive (MS-Pro Seal—Bostik®), suited to several bonding applications (e.g., expansion joints and connecting joints, joints and sealing for building materials, and metals applicable in severe environmental solution), was used. The structure of an MS polymer consists of a polyether backbone and silane terminal functionality. MS polymer's polyether main chain provides low viscosity, low glass transition temperature, and flexibility over a wide temperature range.

Physical and mechanical properties are reported in Table 2.

Table 2 Physical and mechanical properties of MS polymer-based adhesive

MS polyether-based adhesive properties	
Water resistance	Very good
Temperature resistance	−40°–+100°
UV resistance	Very good
Chemical resistance	Good-temporary loads
Density (g/cm^3)	1.4
Hardness (shore A)	30
Tensile strength (MPa)	1.5
Strain max acceptable	35 %
Strain at break	300 %
E (MPa)	0.65

2.2 Joint preparation

The investigation has been carried out on unsymmetrical single-lap joints with total thickness of 2.5 mm. Metal surfaces were prepared by sandblasting (grinding paper P180), followed by a cleaning with acetone, and air drying.

Roughness measurements were performed in different areas, along three different directions, of the same surface in order to verify the treatment uniformity, and the average roughness values "R_a" were calculated. The experimental results showed small spreads, always lower than 10 %. The R_a values were equal to 1.13 μm.

An adhesive layer has been spread on the aluminum alloy surface, covering an overlapping area of (25 × 25) mm^2 with a thickness of 0.2 mm. The adhesive thickness was obtained through the use of regulatory plates [42] with thicknesses of 1.7 and 1.2 mm, for St1/Al1.5 and St1.5/Al1, respectively. MS Pro-Seal is a moisture cure adhesive. At room temperature (about 25 °C) and 50 % relative humidity, MS polyether adhesive have generally the skin time about 10 min and cure 1.5 mm per day. Then, the carbon steel sheet has been put on top and a certain pressure has been applied to achieve a uniform adhesive thickness. The adhesive complete curing is completed after the clinching operation by an electro-hydraulic riveting system. The duration of the clinching process was about 2 s. The equipment (Textron Fastening

Table 1 Chemical composition and mechanical properties of the employed materials

Properties	AA6082	Carbon steel A570
Chemical composition (% weight)	Si = 0.5, Fe = 0.5, Cu = 0.1, Mn = 0.4, Mg = 0.6–1.2, Cr = 0.25, Zn = 0.2, Ti = 0.1, and Al = balance	C = 0.3 Mn = 0.8 P = 0.04 Si = 0.25 Fe = balance
Yield stress (MPa)	224	590
Hardness	BHN = 60	BHN = 162

System) was supplied by a hydraulic motor (230 V, 50–60 Hz) with an electro-hydraulic valve necessary to vary the pressure applied on the punch.

The bottom die has moving blades, which expand and direct the flow outward forming a strong round clinch. The extensible die joint tests were carried out using the geometries proposed by the producer. As proposed by the manufacturer, the choice of the extensible die was also selected as a function of the range of the total thickness of the sheets to be joined (2÷3 mm). Diameter of the punch is 5 mm, and height and diameter of the die are 1.38 and 6.5 mm, respectively. Figure 1 shows tool geometry in the clinching joint forming. The shape of die allows to optimize all the clinching parameters by setting the pressure to be applied on the punch. The calibration of the clinching system was performed in order to match between the load applied on the punch and the oil pressure.

A PC acquired data from a dynamometer connected to clinching equipment. At constant pressure, the load curves were almost coincident, while at increasing oil pressure, the maximum load values have increased. The curve, interpolating the average values of the maximum loads (kN) for each selected pressure (bar), was a straight line, whose equation is $y = 0.0875x + 2.7014$.

Clinched joints were realized with two different combinations of thickness code, St1.5/Al1 (mm) and St1/Al1.5 (mm), where St stands for the steel sheet at top and Al for the aluminum alloy; this latter is always placed at the bottom during the clinching procedure. The number following the sheet is related to its thickness. In Table 3, details of coded configuration are reported.

The working pressure was 300 bar for both St1.5/Al1 (mm) and St1/Al1.5 (mm), and so, the forming force was 28.95 kN. Prior to the clinched sample preparation, several attempts were done at varying the oil pressure to optimize the pressure for both configurations.

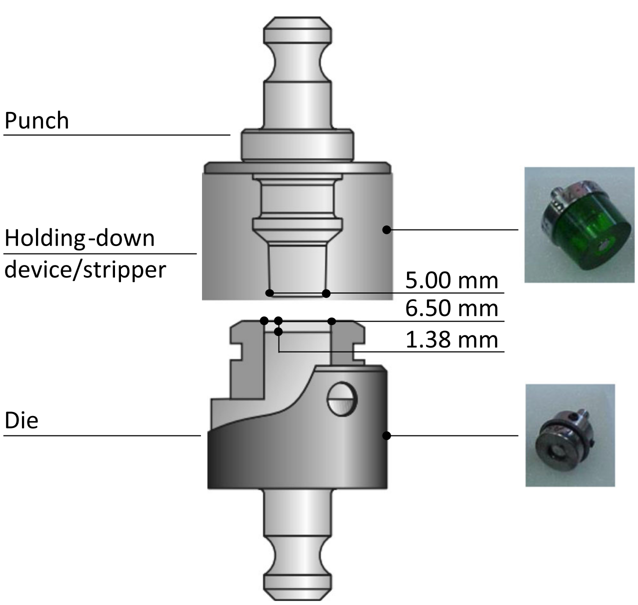

Fig. 1 Tool geometry of clinching process

Table 3 Code configuration of clinched joints

Code	Upper sheet		Lower sheet	
	Metal	Thickness	Metal	Thickness
St1.5/Al1	Carbon steel	1.5	Aluminum	1.0
St1/Al1.5	Aluminum	1.0	Carbon steel	1.5

The geometry of clinched single-lap joint is shown in Fig. 2. Five samples for each joint configuration and for each ageing time were realized for a total of 80 samples. Of ageing time, 0, 1, 2, 3, 5, 7, 10, and 15 weeks have been chosen to evaluate the damage evolution of the samples.

2.3 Ageing treatment

The samples were exposed to critical environmental conditions following the ASTM B 117 standard [43]. A 5 % NaCl salt fog was used (pH between 6.5 and 7.2). In the climatic chamber, the samples were aged continuously at a temperature of 35 °C.

At each fixed ageing time, five specimens of each configuration were removed from the chamber and mechanically tested. Then, the samples, accurately washed and dried, were preserved in a sealed plastic storage bag with silica gel desiccant to ensure no further corrosion phenomena during storage; moreover, appropriate actions have been taken to avoid the introduction of other variable factors, such as the control of the environment conditions.

2.4 Single-lap joint tests and statistical analysis

Shear tests of single-lap joints were performed, according to ISO/CD 12996 [44], by means of a Universal Testing Machine (Zwick-Roell Z250) equipped with a 50-kN load cell at a crosshead rate of 1 mm/min (displacement control test).

The analysis of variance (ANOVA) was performed by Minitab® software to analyze the influence of the two factors, thickness combinations and ageing time, on the mechanical properties of the joint.

3 Results and discussion

3.1 Single-lap shear tests

Figures 3 shows the load versus displacement trends of the single-lap shear tests for two joint configurations at increasing ageing time.

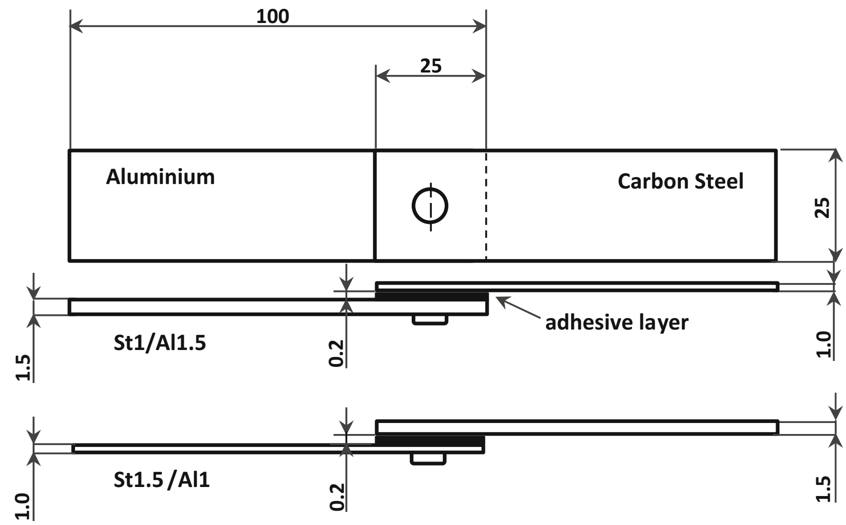

Fig. 2 Geometry of the sample (size in mm)

The resistance of the hybrid joints decreases over time due to ageing in salt spray environment. The maximum load is heavily influenced by degradation due to critical environmental conditions. At the same time, the load/displacement trend decreases significantly at increasing ageing time.

In order to better understand the relationship between mechanical performances, structure, and degradation of the hybrid joints, a preliminary description of damage evolution of single-lap shear joints is performed.

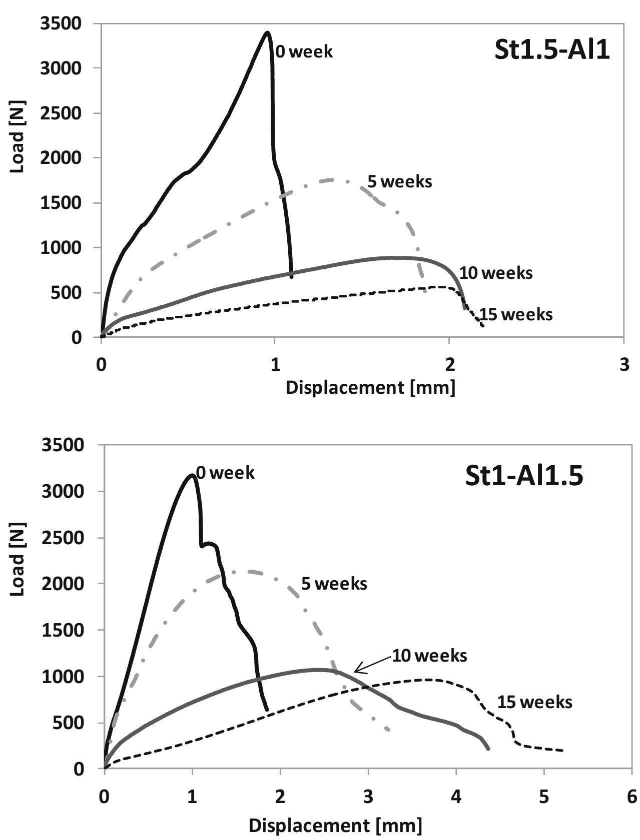

Fig. 3 Typical load/displacement trends for the hybrid joint configurations

For all samples, the load/displacement trends, at low displacement, show a linear increase of the load. In this phase, the joint resistance is due both to the adhesive effect, thanks to the bonding interlayer between the dissimilar metal sheets, and to the contact pressure between aluminum steel sheets induced by the forced interlocking.

Afterward, at higher displacement, the relationship between load and displacement became not linear. The asymmetrical configuration of joint at increasing of the load leads to a significant bending deflection at the end edge of the sheets. The clinching section begins to twist, supporting completely the mechanical stress during the shear. This induces local detachment of bonding interlayer where interlocking force between the sheets is not optimal, thus reducing the global stiffness of the joint. This is evidenced by the reduced slope in the curve trends (Fig. 3), much marked for the St1.5/Al1 samples than St1/Al1.5 ones. When the maximum load is reached, the fracture occurs for unbuttoning of the samples. This phase is followed by an abrupt reduction of the load, and the mechanical stability of the joints is critically prejudiced. This phenomenon is more relevant in St1.5/Al1 set, where the unbuttoning failure takes place with small deformations (displacements up to 2.2 mm). Instead, in St1/Al1.5 batch, the clinching button partially remains anchored to the bottom aluminum plate due to aluminum greater thickness. The complete detachment between metal sheets occurs with an additional plastic deformation at the neck thickness influencing circular region of the button base [45]. The cracks around the button propagate along the circumference of the neck of the upper sheet up to cut it. Thus, the mechanical failure, identified by a drastic load reduction, occurs at greater deformations (displacements up to 4.5 mm).

In St1.5/Al1 hybrid joints, the unbuttoning failure mechanism occurs because the St upper sheet is thicker, and due to

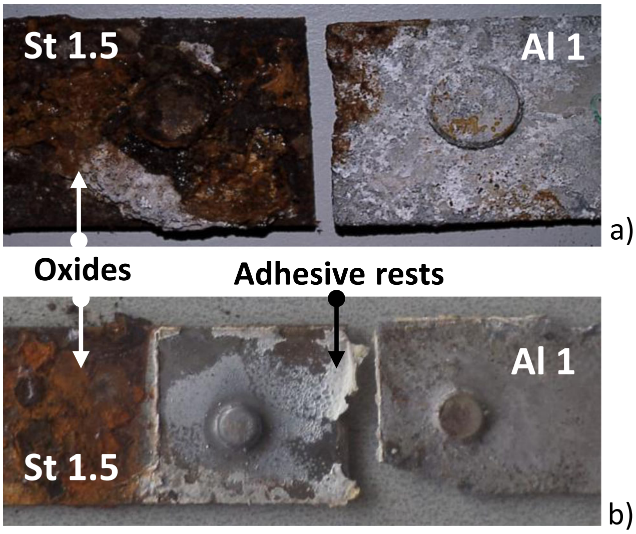

Fig. 4 Comparison of failure surface of the St1.5/Al1 joints at ageing 5 weeks, **a** without adhesive and **b** with adhesive

its low ductility, the clinched button will not acquire completely the typical "S" shape in the cross section. This entails a reduction of interlocking force between the sheets inducing a premature fracture for unbuttoning. This behavior also occurred in St1.5/Al1 clinched joints (without adhesive interlayer) as shown in Fig. 4a, where a reference failure surface of a St1.5/Al1 clinched joint after 5 weeks of ageing is reported. The presence of aluminum oxide in the overlapping area reduces the interlocking force between the sheets and favors their detachment at lower load [41]. Figure 4b shows St1.5/Al1 hybrid joints also at same ageing time, 5 weeks. It is evident that no oxide layer is present on the overlapping area confirming the good protective action offered by the adhesive interlayer. The failure occurred mainly for unbuttoning without the action of the oxide layer at the interface. The presence of the adhesive interlayer reduced significantly galvanic corrosion phenomena. For these samples, the premature fracture could be related to the not well-pronounced S shape in the clinched profile as it happens in the pure clinched joints. At increasing time, the adhesive degrades adsorbing water and thus plasticizes. Therefore, the adhesive strength between substrates decreases. This behavior justifies the progressive load reduction during ageing time, although few evident corrosion phenomena were identified in the hybrid joints, especially at medium ageing time.

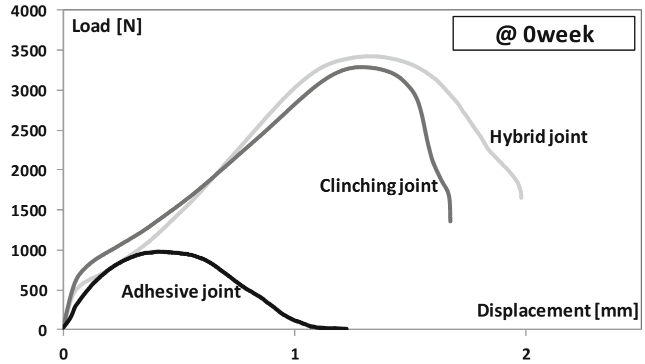

Fig. 6 Typical load shear/displacement trends of adhesive, clinching, and hybrid joints in St1.5/Al1 configuration

At higher ageing time, the load/displacement trends, shown in Fig. 3, present a significant reduction of the maximum load and an increase of the displacement at failure for all batches. This behavior is related to the degradation effect induced by corrosion phenomena; in particular, the electrochemical corrosion coupled with the advanced plasticity degradation of the bonding interlayer stimulate the reduction of the interlocking force and increase the mobility in the overlapping/button area, consequently favoring the premature fracture insurgence at lower values of loads.

After 10 weeks, for both hybrid joint batches, the degradation of the adhesive became relevant, as shown in Fig. 5. The water penetrated in the joint overlapping area and galvanic corrosion at aluminum/steel interface have taken place.

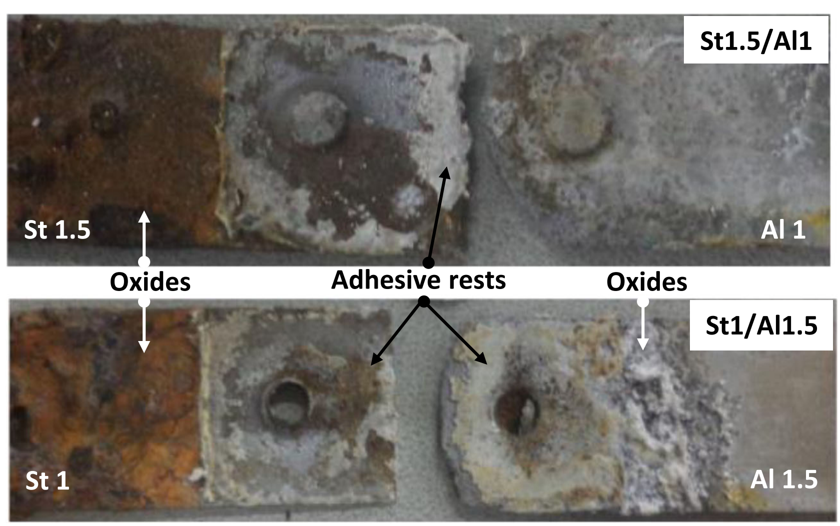

Fig. 5 Comparison of failure surface of the hybrid joints at ageing 10 weeks

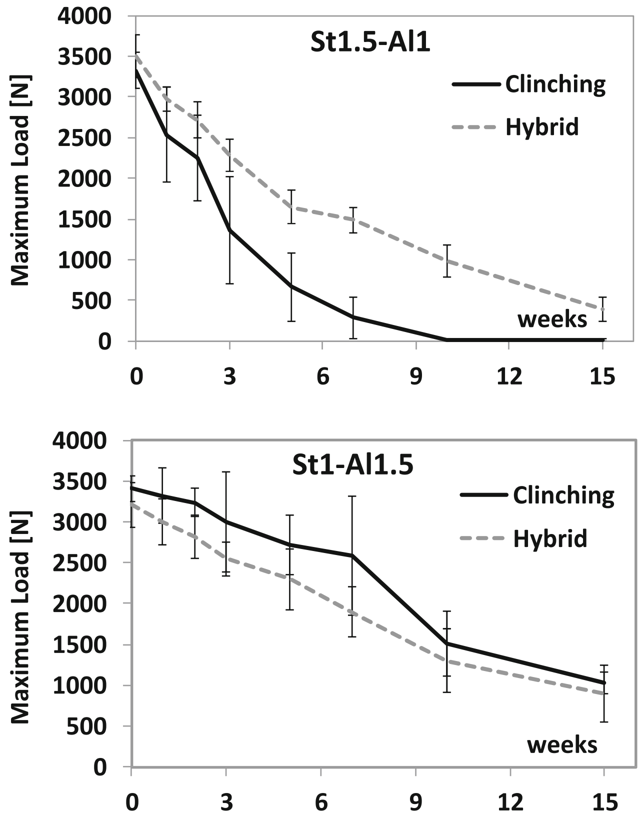

Fig. 7 Typical trends for the hybrid and clinching joint configurations

These local corrosion phenomena accelerate the mechanical degradation of the joints.

3.2 Mechanical versus adhesive/mechanical (hybrid) joints

In a previous work [40, 41], the mechanical joints with the same two investigated configurations have been tested at long ageing time, evidencing a significant durability difference, due to the enhanced corrosion phenomena in the configuration with a lower aluminum thickness (St1.5/Al1).

Figure 6 shows the typical load/displacement curves of adhesive, clinching, and hybrid joints at 0 week in the St1.5/Al1 configurations. MS polymer adhesive has a high grip, excellent toughness, and flexibility, but its tensile strength is smaller than a structural adhesive. In investigated hybrid joints, the adhesive interlayer does not increase very much the mechanical strength of clinched joint, as shown in Fig. 6.

As highlighted by T. Sadowski et al. [46], the use of a flexible adhesive in clinched joints does not influence the strength of the joint by increasing it. In fact, in our clinched and hybrid joints, the shear curves were comparable. The application of the adhesive primarily allows to reduce galvanic corrosion phenomena by electrically insulating the interface between metal plates.

In Fig. 7, the comparison of maximum loads of hybrid (adhesive/mechanical) and pure mechanical clinched joints, with the same materials and configuration, is shown.

For the St1.5/Al1 configuration, we can observe that the presence of the adhesive at the metal interface slightly influence the failure load of unaged and of fully aged samples. The action of adhesive interlayer retards the penetration of metal oxides within the overlapping interface. The outer surfaces of clinched area are rather more exposed to corrosion phenomenon. In particular, the oxides, deposited near to the top of the button, will migrate more rapidly toward the interior of the button resulting in the thinning and failure. For this set, the unbuttoning is the frequent failure mode; at higher ageing time, the neck failure is sometimes verified. The St1/Al1.5 set showed a good mechanical resistance up to 7 weeks due to the higher thickness of aluminum sheet than St1.5/Al1 set. After 10 weeks (seen in Fig. 5), both corrosive phenomena and adhesive degradation are advanced, such as to compromise the mechanical resistance of the joints.

The clinch joint parameters are the axial total thickness of the sheets “*x*,” the thickness of the upper sheet “*th*” (also called neck thickness), and the clinch lock (undercut) “*cl*.”

The clinched joint strength mainly depends on the neck thickness (*th*) and the clinch lock (*cl*), as shown in Fig. 8a.

On St1/Al1.5 clinched joints, unbuttoning failure mechanisms were observed, but they have presented good mechanical performance and better durability despite corrosive phenomena. This effect is due to thin carbon steel sheet at the top side that has favored a good interlocking force between the

Fig. 8 The clinched joint parameters, without (**a**) and with (**b**) adhesive

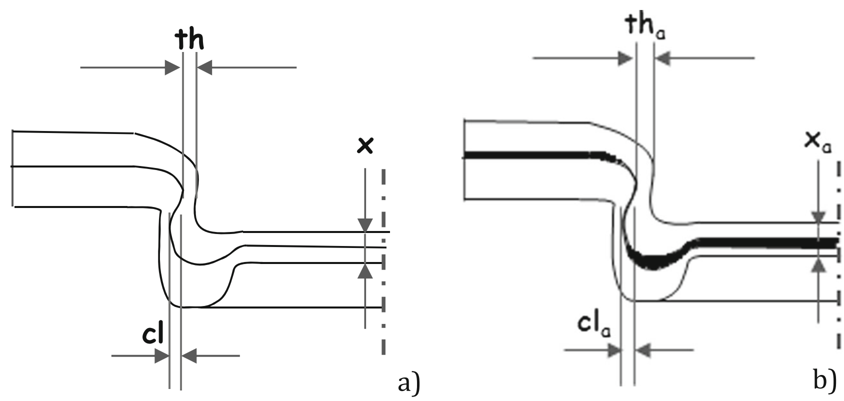

Table 4 Mean loads and standard deviations for the hybrid and clinching joint configurations

	St1/Al1.5				St1.5/Al1			
	Hybrid		Clinching		Hybrid		Clinching	
Week	F_{mean} (N)	Standard deviation	F_{mean} (N)	Standard deviation	F_{mean} (N)	Standard deviation	F_{mean} (N)	Standard deviation
0	3210.2	±275	3409.3	±162	3498.7	±260	3326.7	±224
1	3005.2	±284	3321.6	±334	2979.2	±150	2537.8	±586
2	2820.6	±259	3238.2	±175	2720.3	±230	2252.3	±526
3	2554.4	±209	3002.5	±610	2282.5	±195	1361.1	±656
5	2305.3	±368	2723.7	±361	1648.9	±210	665.3	±420
7	1910.1	±303	2589.4	±728	1487.4	±160	288.8	±250
10	1298.8	±389	1504.4	±396	984.5	±193	16.6	±22
15	900.7	±348	1031.4	±134	389.6	±143	14.3	±19

sheets, and a thick aluminum sheet at the bottom side flows in the radial direction along the walls of die in the necessary time to become thinner, thus obtaining the typical S shape in cross section with appropriate values of *th* and *cl*. Conversely, in the St1.5/Al1 clinched joints, the thicker carbon steel sheet and its low ductility will result in less strong interlocking in the cross section. So, the undercut (*cl*) values will be lower and the typical S shape in the area of clinching will be less pronounced. At higher ageing times, the combined action of two corrosive phenomena, such as the formation of aluminum oxides that tend to accumulate in the overlapping joint region (reducing the interlocking and thus *cl*) and a progressive thinning of the aluminum plate, will reduce the durability of joints by influencing failure mechanisms.

The clinching process before adhesive curing can be a little more effective for the clinched joint performance with respect to the procedure of adhesive curing before clinching [23]. Adhesive layer can be like a lubricant during clinching, and it can facilitate forming the clinch indentation, and then after curing, it gives strong adhesive forces between sheets in the clinch cavity. The technique of clinching before adhesive curing creates also more stiff joints. The adhesive interlayer does not involve changes in the geometry of the cross section of the clinched joint. The th_a and cl_a values (Fig. 8b) do not differ much from those of clinching joints without adhesive. The forming force for hybrid joints involves the spreading of adhesive far from the typical area S toward the overlapping area around the neck and the button of clinching, realizing at times in the bottom corner of the joint cavity as a fold.

In the St1/Al1.5 hybrid joints, the thinning of th_a is due to oxide layers that are deposited in the upper side of the clinch button that weakens interlocking leading to fracture.

A different behavior was observed for St1.5/Al1 hybrid configuration. The presence of the adhesive not only inhibits the galvanic corrosion phenomena but also slows down the dissolution of the Al lower sheet, which has a thickness smaller than other batch. The failure mode is mainly unbuttoning of upper sheet from the lower one due to the joint small undercut (cl_a). A lower variability (standard deviation) of St1.5/Al1 data is shown as a consequence of a better stress distribution near the clinched button, as reported in Table 4. At increasing ageing time (i.e., 10 weeks in Fig. 5), the phenomena of corrosive dissolution in aluminum plate diffuse fast due to the presence of Al thinner thickness with respect to St1/Al1.5 ones, compromising mechanical stability of the joints. Thus, the hybrid joints evidence a better mechanical stability at very high ageing time. Also, in this case, a lower variability is attained by the presence of the adhesive.

In St1/Al1.5 hybrid batch, the standard deviation values are larger at high ageing time because the advance of corrosive phenomena especially in the steel upper sheet involves, in some cases, thinning of th_a and so to neck failure and in other cases, the break of the hybrid joints in climatic chamber.

Table 5 ANOVA of hybrid joint data

ANOVA hybrid P[N] versus thickness; weeks					
Factor		Type	Levels	Values	
Thickness		Fixed	2	1 and 2	
Weeks		Fixed	8	1, 2, 3, 4, 5, 6, 7, and 8	
Analysis of variance for P[N]					
Source	*df*	SS	MS	*F*	*P*
Thickness	1	13,261	13,261	0.10	0.752
Weeks	7	61,512,989	8,787,570	66.47	0.000
Error	71	9,386,269	132,201		
Total	79	70,912,519			

$S = 363.595$, $R^2 = 86.76$ %, and R^2 (adjusted) = 85.27 %

Table 6 ANOVA of clinched joint data

ANOVA clinching P[N] versus thickness; weeks

Factor		Type	Levels	Values	
Thickness		Fixed	2	1 and 2	
Weeks		Fixed	8	1, 2, 3, 4, 5, 6, 7, and 8	
Analysis of variance for P[N]					
Source	*df*	SS	MS	*F*	*P*
Thickness	1	3,256,775	3,256,775	24.59	0.002
Weeks	7	15,192,046	2,170,292	19.39	0.001
Error	7	927,129	132,447		
Total	15	19,375,950			

Source: [40]

$S = 363.9$, $R^2 = 95.22$ %, and R^2 (adjusted) = 89.75 %

3.3 Statistical analysis

The influence of the two factors, thickness combinations and ageing time, on the mechanical resistance of the joints, has been evaluated by ANOVA (for $P = 0.05$) and performed by Minitab® software. The results are summarized in the following Table 5.

In the following, the two factors "thickness" and "ageing time" are called *thickness* and "*week*," respectively: the first with two levels (level 1 for St1/Al1.5 and level 2 for St1.5/Al1) and the second with eight levels (1 for 0 week, 2 for 1 week, 3 for 2 weeks, 4 for 3 weeks, 5 for 5 weeks, 6 for 7 weeks, 7 for 10 weeks, and 8 for 15 weeks).

In Table 6, the ANOVA of clinching joint data are reported for the comparison with the hybrid joints ones.

From the ANOVA, it resulted that the thickness factor is statistically significant for the clinch joints ($P = 0.002 < 0.05$),

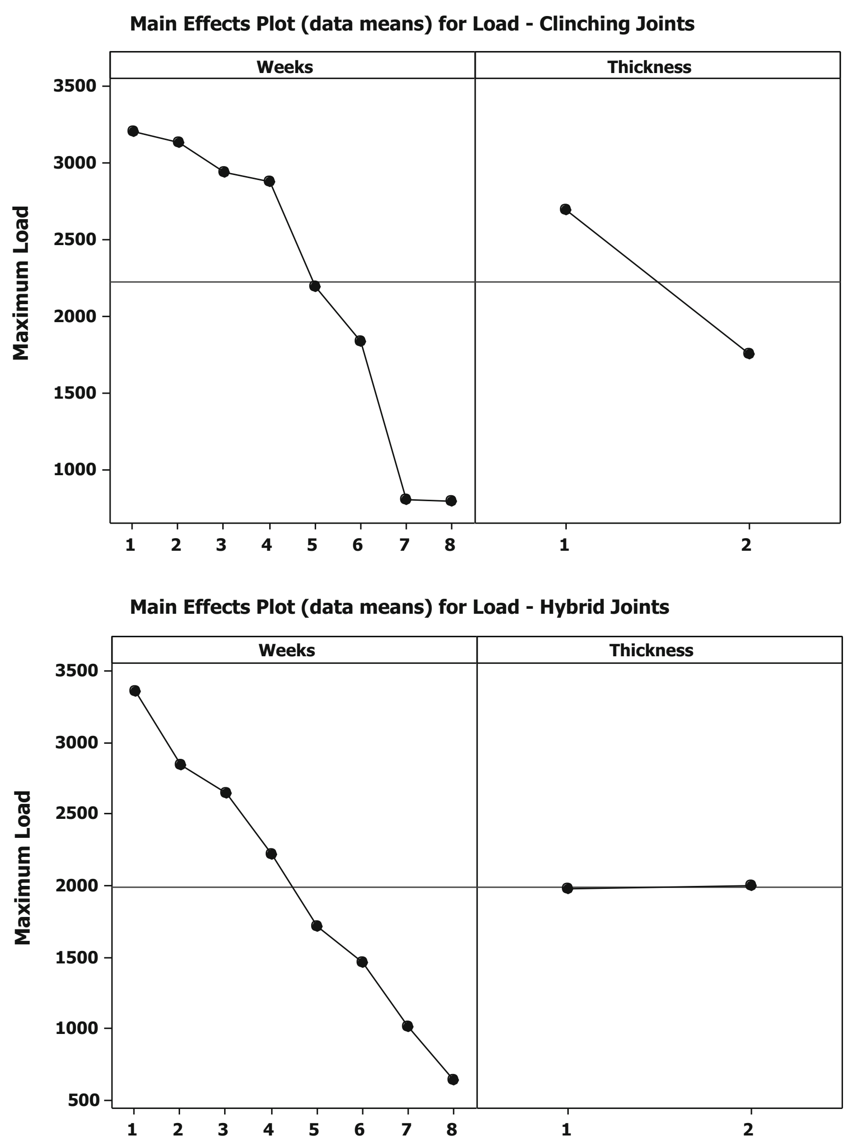

Fig. 9 Main effect plots for the clinching (*up*) and hybrid (*down*) joint configurations

that means the average values of shear loads belong to different populations (St1/Al1.5 and St1.5/Al1); instead, the thickness factor is not significant for the hybrid joints ($P = 0.752 > 0.05$). This result clearly evidences that the presence of the adhesive affects the strength distribution of the joints. Thus, the adhesive homogenizes the mechanical behavior of the two combinations of thicknesses; that is, the mean load values belong to the same population.

Concerning the thickness term, in the statistical analysis, it indicates the total thickness (considering both metal sheets); of course in the case of hybrid joints, this parameter also includes the adhesive interlayer. Therefore, in the clinch joints, the thickness is a statistically significant parameter because the two joint configurations are differently affected by the galvanic corrosion at the interface in overlapping area. When the lower aluminum sheet is thinner, the degradation phenomena are more effective such as to lead to a rapid thinning of the substrate and thus affect the mechanical interlocking. When the lower sheet of aluminum is thicker, the degradation phenomena are less strong and the joints retain a greater mechanical resistance by increasing the ageing time. In hybrid joints, the presence of the adhesive layer in the total thickness of overlapping area makes the thickness parameter statistically not significant; i.e., the two configurations of the joints belong to the same population. In fact, in both joint configurations, the presence of the adhesive layer homogenizes the behavior at break by reducing the effect of the degradation. Then, hybrid joints are less affected by galvanic corrosion compared to clinched joints. Despite thickness parameter (not evidenced as a statically significant variation of failure load at each ageing weeks), the week factor (related to ageing time) is identified as a statistical significant parameter.

In fact, as it was expected, the week factor is significant for both joint types. These facts are evidenced in the main effect plots (Fig. 9). In these plots, the steeper the slope of the line, the greater the magnitude of the main effect.

4 Conclusions

An experimental campaign has been carried out to investigate how the presence of an adhesive interlayer can influence the resistance of hybrid aluminum alloy/steel joints exposed for 15 ageing weeks in salt spray environment. The use of a flexible adhesive does not influence significantly the mechanical performance of the hybrid (adhesive/mechanical clinched) joints. Its presence protects significantly the metal interface from phenomena of galvanic corrosion. The values of the shear loads decrease at increasing ageing time. The mode of failure of the joint hybrids is unbuttoning similarly to those of the pure mechanical clinched joints. Furthermore, the results evidence that a much homogeneous performance in the hybrid joints can be obtained independently from the selected joint configuration; i.e., very low dispersion of the load data is obtained. As confirmed by the ANOVA, only the ageing is a significant factor for hybrid joints when a flexible adhesive is used.

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