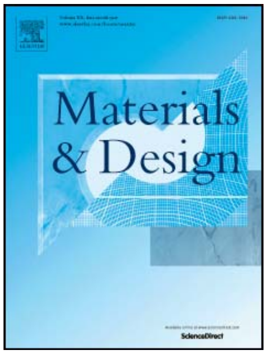

Effect of corrosion degradation on failure mechanisms of aluminium/steel clinched joints

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Effect of corrosion degradation on failure mechanisms of aluminium/steel clinched joints

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Keywords: Clinched joints, durability, corrosion, single lap shear test, failure map.

Abstract

The effect of corrosion phenomena in critical environmental conditions on the mechanical performance of steel/aluminium hybrid joints, obtained by clinching technique, was studied by ageing in salt spray environment. The investigation was carried out on asymmetrical joints with total thickness of 2.5 mm. The joint strength at varying ageing time was determined by means of single lap shear tests.

The experimental results have shown that corrosion degradation phenomena significantly affect the performance and failure mechanisms of the joints, causing premature failure of the joint at very low stress level.

Moreover, it was observed that the joint geometry characterized by thicker aluminium foil, had good durability properties showing acceptable mechanical properties even at long ageing times. The fracture modes have been analysed in all the above mentioned conditions and a failure map, at increasing ageing time, for the two joint geometries has been proposed.

Introduction

In the automotive industry the development of the assembly process is highly evolved, expecially in the manufacturing car body assembly area. Companies operating in this industrial area are strongly stimulated to implement new solutions designed to maximize performance and minimize weights and costs. This resulted in a growing need to design lightweight structures and use of lightweight materials in the manufacture of car bodies [1]. The optimization of a vehicle in terms of cost and performance can be achieved only by using different materials in different positions of the vehicle in order to exploit the peculiar characteristics of each different material optimized to specific use conditions (weight reduction, minimization of overall dimension, performance optimization). Some of these lightweight materials are difficult or impossible to weld with conventional spot welding technique. So, considerable effort has been made for the development of new joining technologies suitable to be use with lightweight materials.

The use of hybrid mechanical joints totally or partially constituted by composite laminates is sometimes an applied solution [2]-[3]-[4]-[5]. The advantages in terms of lightness and formability are considerable, but effective guidelines are necessary in the joint design [6]-[7]-[8].

At this moment steel and aluminium alloys are surely the most important construction materials for mass production of automotive structures [9]-[10]-[11] .

Traditionally, resistance welding and fusion welding have been used in the automotive industry. However, the welding process leads to a local heating of the material that may imply micro-structural or mechanical modifications of the joined materials [12].

The use of asymmetric assembling in the automotive industry has led to the development of various technologies. Friction stir welding [13], laser welding [14], self piercing riveting [15] or mechanical clinching [16] are among the most interesting joining technologies.

Clinching is a well known mechanical joining technology, but only in recent years, the industrial interest regarding this technique is significantly increased due to the possibility to be successfully applied to complement or to replace other joining techniques such as spot welding [17].

Clinching is one of the most common metal joining processes in the manufacturing industry, especially when the assembly does not required the use of additional elements. This joining technique is indicated for coupling, similar or dissimilar, pre-coated or galvanized, sheets usually up to a total thickness of 3 mm [17]-[18]-[19]-[20].

The clinching process is achieved by placing the metal sheets to be joined between a punch and die with a localized cold deformation. The tools typically consist of a punch and a die. A button is formed on the underside and provides an interlock between the plates. The result is an interlocking friction joint between two or more layers of material. A schematic representation of the clinching operation is reported in figure 1.

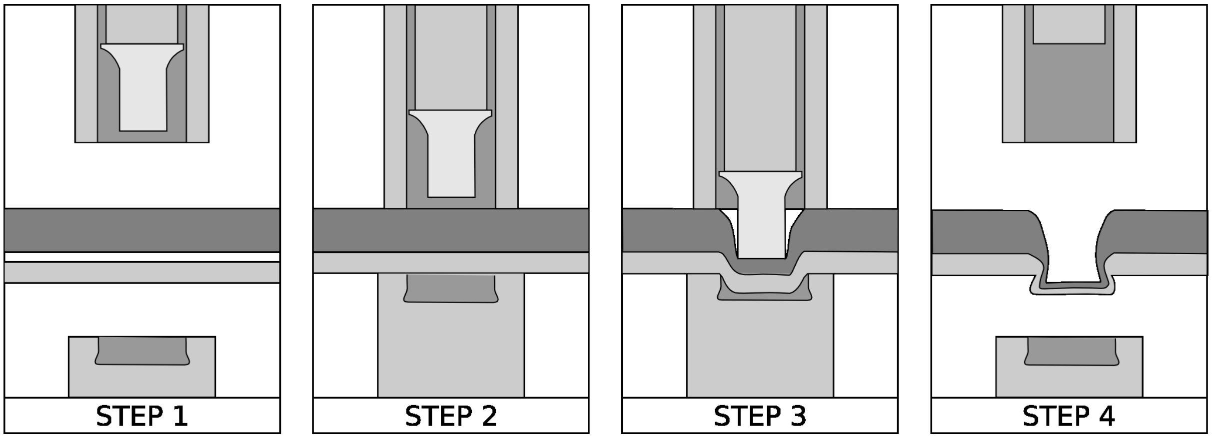


Figure 1: Schematic representation of the clinching operation

The clinching is a technological solution that does not affect the performances and does not introduce physical discontinuity between the constituent materials, in fact it doesn't induce any thermal stresses into the work-piece. The process does not cause heat, splashes, flashes or harmful light.

In the past few years several studies on the behaviour of clinched joints subjected to static loads and fatigue cycles have been published [21]-[22].

Although mechanical clinching has a low running cost, some difficulties were found to apply this technology to dissimilar material sheets (e.g. aluminium alloy with high-strength steel, due to the low ductility of the steel). In the clinching process of high-strength steel, defects occur due to its low ductility [23]-[24], influencing negatively the mechanical performances of the joint.

Furthermore, one aspect that limits the application of this type of joint is its durability in aggressive environmental conditions due to localized corrosion mechanisms [25]-[26].

In fact, the mechanical coupling of steel and aluminium structures increases the risk of galvanic corrosion, due to the different electrochemical behaviour of the two alloys [27]-[28]. Furthermore, the internal stress induced by the cold forming process may facilitate the activation and propagation of cracks due to local stress corrosion cracking (SCC), further reducing the joint durability. The geometrical discontinuity and interstices can intensify the problem, leading to the activation of crevice corrosion phenomena, a form of local corrosion induced by accumulation of electrolyte in the interstices of the joint [29].

The relationship between corrosion and mechanical properties of joined material is not always evident. At the same time the variety of metal panels used in assembly design and the several joining techniques for coupling dissimilar materials makes it very difficult any prediction on long-term performances. It is an important aspect assessing the influence of corrosion behaviour on mechanical performance in order to provide engineering designers and suppliers a better knowledge regarding the selection of appropriate materials to realize homogeneous or heterogeneous joints.

Accelerated ageing tests (i.e. salt fog test) were usually carried out to evaluate the durability of the joints in highly aggressive environments.

LeBozec et al. [30] evidenced loss of mechanical properties of welded joints exposed in an accelerated corrosion test due to corrosion degradation in the overlapped area which induced a modification of the failure mode. Furthermore they observed that the remaining thickness decreased and at the same time the strength loss increased with the exposure time.

Calabrese et al. [31] performed long term ageing tests in critical environmental conditions to evaluate the mechanical durability of aluminium 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. [32] 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 joints durability and electrochemical behaviour of the metal constituents.

However, even if the problems related to the durability in aggressive environment of clinched joints are industrially known [30], in the literature only few works aimed to better relate aspects of corrosion degradation with the mechanical behaviour of the joints are reported.

In this concern, the aim of the present work is to evaluate the effect of the ageing time in salt spray test on the mechanical performances and failure mechanisms of carbon steel/aluminium alloy joints, obtained by clinching. Two combinations of sheet thicknesses were investigated; seven samples for each combination and for each ageing time were realized. The joint resistance has been determined by means of single-lap shear tests. The mechanical behaviour of the joints was related with the observed corrosion degradation mechanisms.

Experimental Part

Materials and Manufacturing

The investigation has been carried out on asymmetrical single-lap joints with total thickness of 2.5 mm. The employed materials, their thickness, chemical and mechanical properties are summarised in Table 1.

	Material	
	AA6082	Carbon Steel A570
Geometry (thickness in mm)	1 and 1.5	1 and 1.5
Chemical Composition	Fe=0.5 Cu 0.1 Si=0.5 Mn=0.4 Mg=0.6 to 1.2 Cr=0.25 Zn=0.2 Ti=0.1 Al=balance	C=0.3 Si= 0.25 Mn=0.8 P=0.04
Hardness	$HBN_{(2.5/62.5/30)}$=60	HV=170
Yield strength (MPa)	224	590

Table 1: Properties of the employed materials

Clinched joints were realized with two different combinations of thickness: St1.5/Al1 [mm] and St1/Al1.5 [mm]; where St is referred to steel sheet at top and Al for aluminium-alloy sheet, this latter is always placed at the bottom during the clinching procedure. The geometry of clinched single lap joint is shown in Figure 2. Ageing time in salt spray cabinet ranged from 0 to 15 weeks (0, 1, 2, 3, 5, 7, 10 and 15 weeks). For each ageing time seven samples of each configuration were prepared.

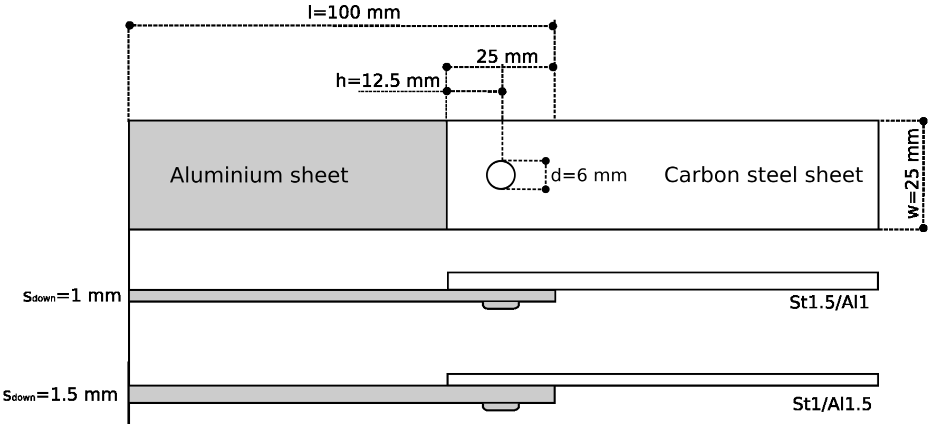


Figure 2: Single lap joint geometry

Clinching Process

The joints were realised by an electro-hydraulic riveting system. The duration of the process was about 2 seconds. The equipment (Textron Fastening 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 maximum operation pressure was 630 bar; the maximum force was approximately 60 [kN]. Prior to the clinched sample preparation, several attempts were done at varying the oil pressure to optimize the pressure for both configurations. The working pressure was 300 bar for both St1.5/Al1 [mm] and St1/Al1.5 [mm].

The use of an TOG-L-LOC die with blades which expand allows to connect metal sheets of different thickness compatibly with the depth of the die (in our case up to 4 mm in total thickness of the connected sheets) allowing a strong circular interlock.

Accelerated Ageing Test

The samples were exposed to critical environmental conditions following the ASTM B 117 standard. The salt fog had a chemical composition of 5% NaCl solution (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, seven specimens of each configuration were removed and mechanically tested. Then the samples, clean and dried, were preserved in a sealed plastic storage bag with silica gel desiccant to ensure no further corrosion during storage; moreover the appropriate actions have been taken to avoid the introduction of other variable factors.

Single Lap Shear Test

Shear tests of single-lap joints were performed, according to ISO/CD 12996, by means of an Universal Testing Machine (Zwick-Roell Z250) equipped with a 50 kN load cell and a cross-head rate of 1 mm/min (displacement control test). The fracture surfaces and corrosion degradation evolution were investigated by using a 3D digital microscope (Hirox KH-8700).

Results and Discussion

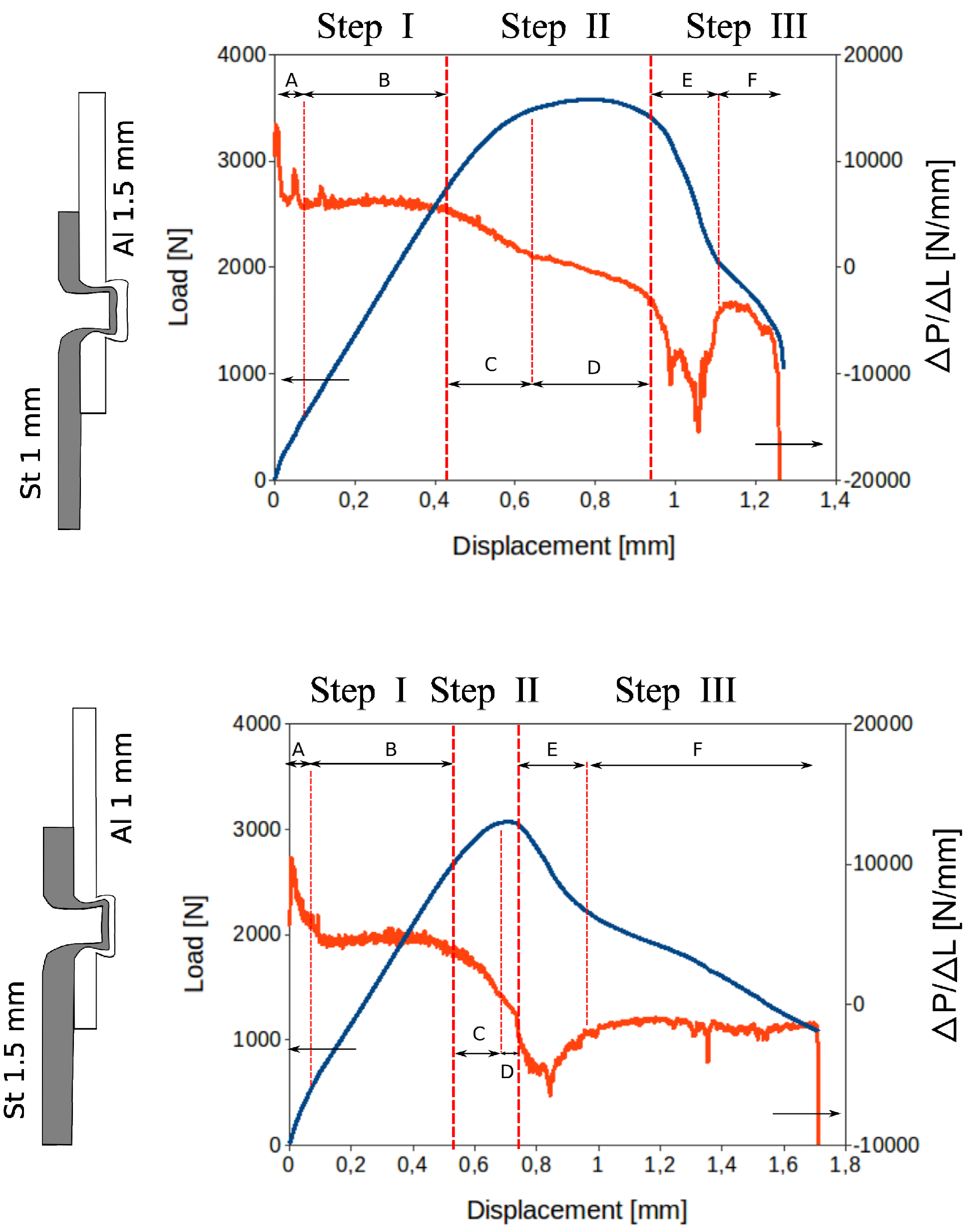


Figure 3: Trends of load (left) and load/displacement slope (right) versus displacement for St1/Al1.5 (upper plot) and St1.5/Al1 (lower plot) at 0 weeks of ageing

The figure 3 shows the trend of the load-displacement curve for both St1/Al1.5 and St1.5/Al1 unaged specimens. In the same graph the slope evolution of the load-displacement curves is reported. Analysing the figure we can identify three main stages:

I. Initial stage. In this stage two sub-steps can be identified. At first, the initial trend is related with mechanical adjustments of the joint-vice system (sub-step A). This sub-step is not representative of the mechanical behaviour of the joint and was not taken into account in the performance evaluation of the clinched joints. Afterwards in the sub-step B a linear increase of the load versus displacement was observed. In this stage the slope ∆P/∆L is quite constant. In this phase the joint resistance is due both to the friction resistance, resulting from the contact pressure between the aluminium and steel sheets induced by forced mechanical joining and a shear resistance offered by the clinched button (figure 4a).

II. Maximum load Stage: In this stage the load-displacement curve become not-linear and a progressive reduction of the slope ∆P/∆L is observed (sub-step C). This behaviour can be related with a progressive loss of adhesion between the sheets due to a significant bending deflection at the end edge of the sheets as a consequence of the asymmetrical configuration of the single lap joint. The mechanically connected section begins to twist, losing in this way the effect of contact friction on the total resistance of the joint. In this phase the mechanical behaviour of the joint is strictly suffered by the clinched button (figure 4b). In sub-step D, the load reached a maximum (about 0.8 mm of displacement for two samples). Increasing the deformation of the joint in the load/displacement curve a plateau was observed in correspondence of the maximum load, evidencing a progressive failure mechanism of the joint. For the specimens St1/Al1.5 this region is very wide due to a bearing phenomenon around lower button on aluminium side induced by a sliding action offered by the upper carbon steel sheet. In this region a progressive plastic deformation of the aluminium sheet joint was observed, the aluminium button loses its circularity (figure 4c). Vice versa for the specimens St1.5/Al1 this region is much reduced because the resistance offered by the aluminium sheet is lower than St1/Al1.5 set, facilitating premature mechanical damaging of the clinched joint.

III. Residual resistance stage: Afterwards the joint is critically damaged, as evidenced by the reduction of ∆P/∆L ratio over 50% compared with its maximum value (sub-step E). The residual strength of the joint progressively decreases. However, the load does not undergo a drastic reduction, but a gradual evolution of the damage as a result of unbuttoning was found. For St1/Al1.5 samples, sometimes, cracks in the button neck of carbon steel button was observed. Thus favouring neck failure mechanism, characterised by reduced deformations to failure, as reported in figure 3. A plateau of ∆P/∆L ratio was observed (sub-step F). This phase, more relevant in St1.5/Al1 samples, is due to the fact that the clinched button partially remains anchored to the bottom aluminium plate. Therefore to obtain the complete detachment of aluminium and steel plates an additional plastic deformation at the neck of the button should occur (figure 4d). Finally, at greater deformation, a full complete fracture of the joint takes place with drastic load reduction of the load. The unaged samples have evidenced a final neck cracking failure mechanism.

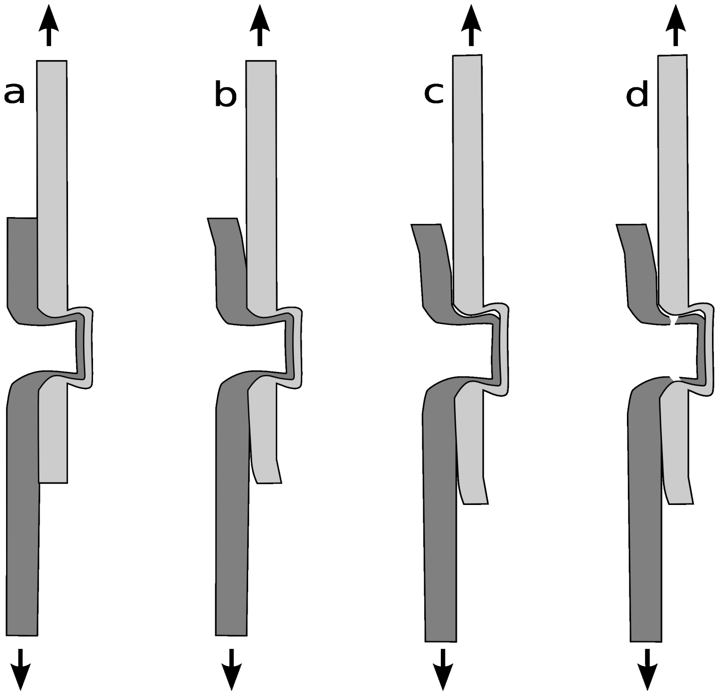
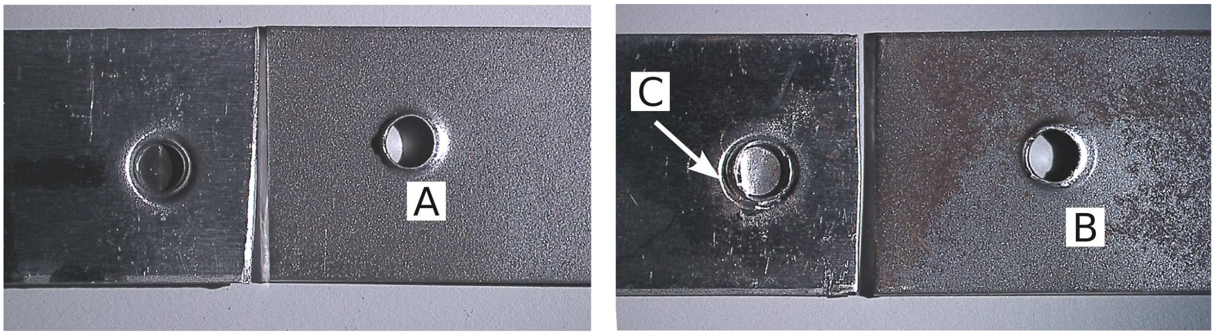


Figure 4: Scheme of deformation evolution of unaged clinched joint during single lap shear test



a) *b)*

Figure 5: Image of failure surface of the clinched joint without ageing (0 Weeks samples) a) St1/Al1.5 b) St1.5/Al1

Figure 5 shows the failure surface of the unaged clinched joints. All batches evidenced fractures on the carbon steel neck. The St1/Al1.5 joints have evidenced a sharp fracture that affects the circular region of the button base (point A in figure 5a). Instead St1.5/Al1 joints have evidenced a more complex failure mechanism. The neck failure (point B in figure 5b) is combined with a plastic deformation of aluminium button (point C in figure 5b) inducing a mixed failure mechanism.

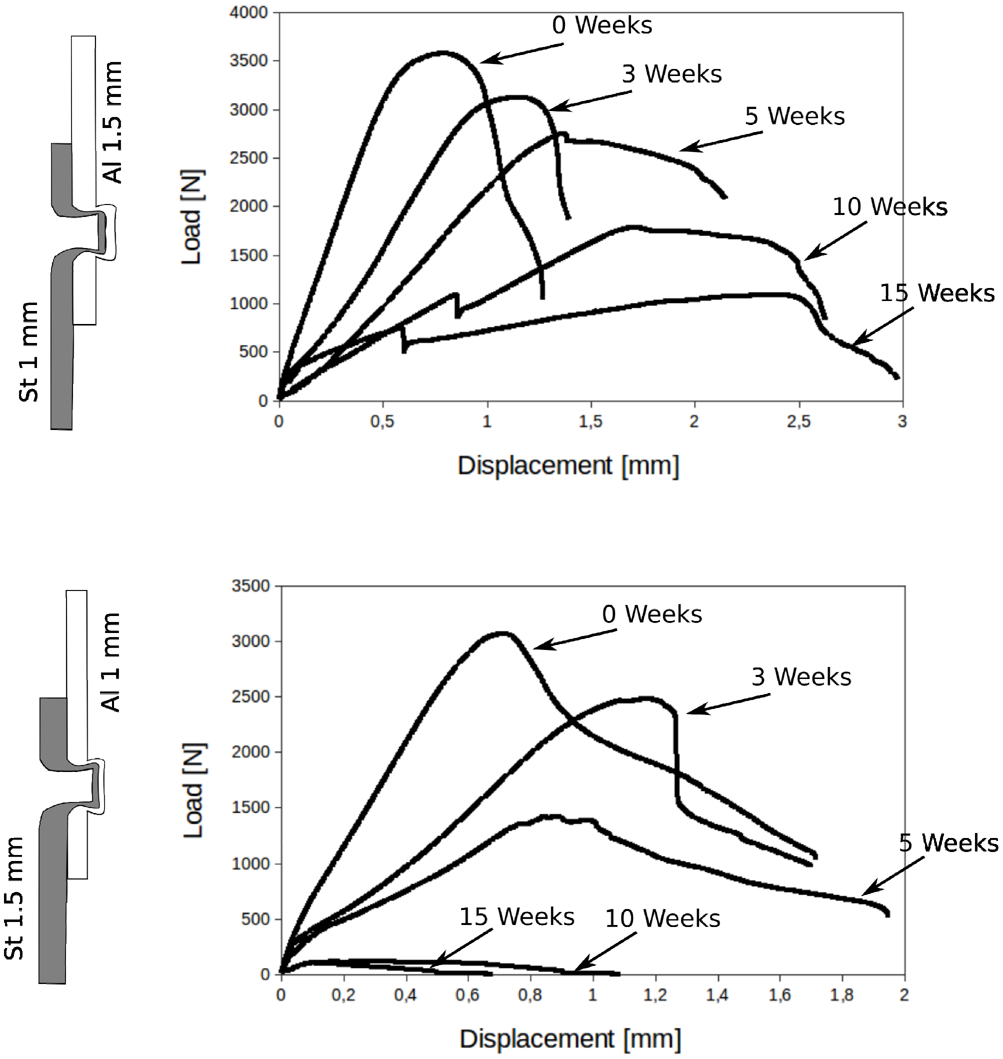


Figure 6: Trends of load versus displacement for St1/Al1.5 (upper plot) and St1.5/Al1 (lower plot) at increasing ageing weeks

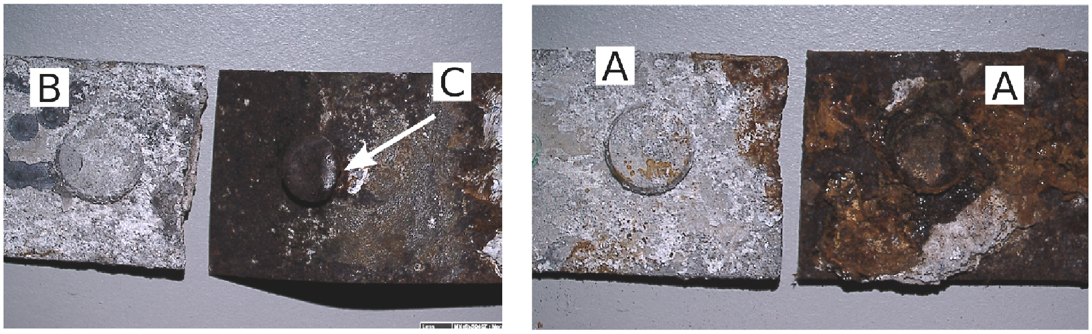
The figure 6 shows reference load–displacement curves for the St1/Al1.5 and St1.5/Al1 samples at increasing ageing time. The curves evidenced both a strong reduction of the slope and of the failure load at increasing ageing time. The ageing in salt spray chamber significantly decreases the mechanical properties of both clinched joint configurations due to a premature fracture induced by corrosion phenomena. Furthermore all samples usually evidenced an increase of deformation to failure at increasing ageing time.

At short ageing times the failure mechanisms, observed on the samples, are partially or totally due to carbon steel neck failure. In absence of significant corrosion phenomena the interlocking force between the metal sheet is high, thus favouring the failure of the upper sheet of the clinched joint [24].

Furthermore, analysing figure 6, the step III of the load/displacement curves (identified in figure 3), related with the progressive evolution of damaging in correspondence of the button, appears to be larger at increasing of ageing time. This phenomenon is associated with a gradual degradation of the mechanical joint that reduces its performance. Due to galvanic coupling on the dissimilar metal joint, the aluminium alloy will act as anode instead the carbon steel sheet will act as cathode [28]. This implies an acceleration of the dissolution kinetic of the anode (aluminium alloy sheet).

Two phenomena are involved in this stage: the formation of aluminium oxides that tends to accumulate in the overlapping joint region (reducing the interlocking), and a progressive thinning of the aluminium plate that takes place as a result of its electrochemical dissolution. The combined action of these corrosion phenomena reduces the durability of the joint in this aggressive environmental conditions and at the same time influences significantly the failure behaviour of the joints.

Such effect is particularly evident for the St1.5/Al1 joint samples. This batch has showed lower failure loads than St1/Al1.5 ones. This is due to the unbuttoning failure mechanism observed for this class of joints. The upper carbon steel sheet is very thick, and due to its low ductility, the clinched button will get a less strong interlocking (determined by the typical “S” shape) in the cross-section that favours an optimal stress transfer between the joined sheets. This will induce a premature fracture by unbuttoning mechanism (point A figure 7b). The presence of aluminium oxide in the overlapping area enhances this effect. On St1/Al1.5 unbuttoning failure mechanisms was observed (point B in figure 7a). But due to a still acceptable interlocking strength between the metal sheets, also a plastic deformation in the button was observed (point C in figure 7a).

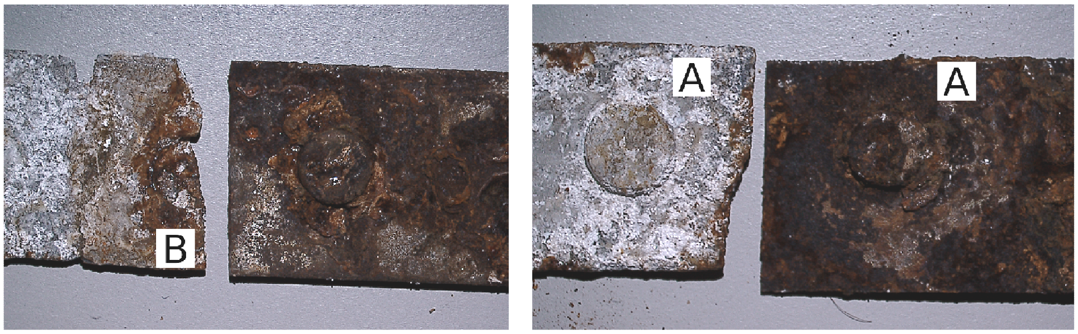


a) b)

Figure 7: Image of failure surface of the clinched joint at five ageing weeks a) St1/Al1.5 b) St1.5/Al1

At long ageing time, the dissolution of aluminium sheet becomes significant and the joint mechanical stability is compromised and a very low failure load was observed. At same time, the corrosion dissolution is so deeply extended that occasionally a premature rupture of some joints have taken place in the salt spray chamber.

St1/Al1.5 joints have evidenced a better durability. A thin carbon steel sheet at the top side has favoured a good interlocking force between the sheets and a thick aluminium sheet at the bottom side flows in the radial direction long the walls of die in the necessary time to become thinner, delaying the drastic reduction of the failure load observed instead for the St1.5/Al1 joints already at 10 ageing weeks.



a) b)

Figure 8: Image of failure surface of the clinched joint at 15 ageing weeks a) St1.5/Al1 b) St1/Al1.5

In figure 8b the images of the observed unbuttoning failure mechanism for St1/Al1.5 sample at 15 ageing weeks are reported. Instead St1.5/Al1 samples have evidenced a mixed shear-out/net-tension failure mechanism. This mechanism could be classified as cleavage failure of the mechanical joint [33]. This failure mode is characterised by large dissolution of the thin lower aluminium sheet until the button clinched joint is reached (point B in figure 8a).

A rate of load loss, defined as [(Pmax(unaged) – Pmax(aged)]/Pmax(unaged), was calculated in order to better identify the evolution of the mechanical performance of the various joints in function of the ageing time. The results are summarised in figure 9.

The specimens with a thin steel sheet (St1/Al1.5) have showed a better durability as a function of ageing time, with low rate of load loss. Conversely the specimens characterized by a thicker steel sheet (St1.5/Al1) have showed a very rapid degradation at increasing ageing weeks. This batch has evidenced, after only 3 ageing weeks, a reduction of almost 50% maximum load respect to that one of the unaged joint. After 10 weeks these joints loose completely their structural features due to a drastic reduction of about 95% the maximum load. Instead St1/Al1.5 batch presents a more gradual degradation of its mechanical performance. After 3 weeks the load reduction was only about 20% respect to unaged conditions. Finally, after 15 ageing weeks these joints, although deteriorated, were still not mechanically compromised and they presented load resistance of about 30%-40% of the unaged samples.

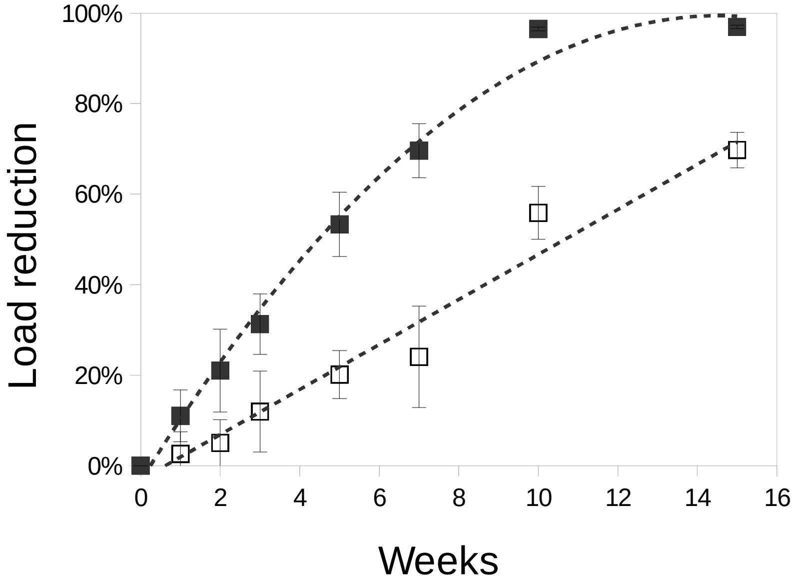


Figure 9: Maximum Load reduction (%) versus ageing time

In figure 10 the cross sections of clinched joints at increasing ageing time are reported. Clinched profile of the joint for St1.5/Al1 and St1/Al1.5 at 0 weeks can be analysed from the images.

The St1.5/Al1 sample, characterized by a thicker upper carbon steel sheet, presents a poor mechanical connection of the sheets. The not well pronounced "S" shape in the button zone, at the interface of the two sheets, indicates a low interlocking of the clinched joint. Instead, St1/Al1.5 sample, characterized by thinner carbon steel sheet, evidences a better joint interlocking. The carbon steel sheet during punch pressure is deformed sufficiently to ensure good deformability also of the underlying aluminium sheet.

After two ageing weeks of ageing the specimens St1.5/Al1 evidenced the formation of oxides at the interface between the two laminae (point A in Figure 10). This implies water permeation in the interstice caused by the low interconnection between the metal sheets. With increasing ageing time samples progressively evidenced significant corrosion damaging.

In particular, after five weeks the crevice corrosion accelerates localised dissolution phenomena at the metals interface. In these conditions a interlocking loss occurs evidenced from loosening at the sheet edges (point C in Figure 10) and in correspondence of the clinching button (point D in Figure 10). After 10 weeks the degradation phenomena are intense and such as to induce the mechanical instability of the joint at very low load levels, (point E figure 10), as confirmed in figure 6.

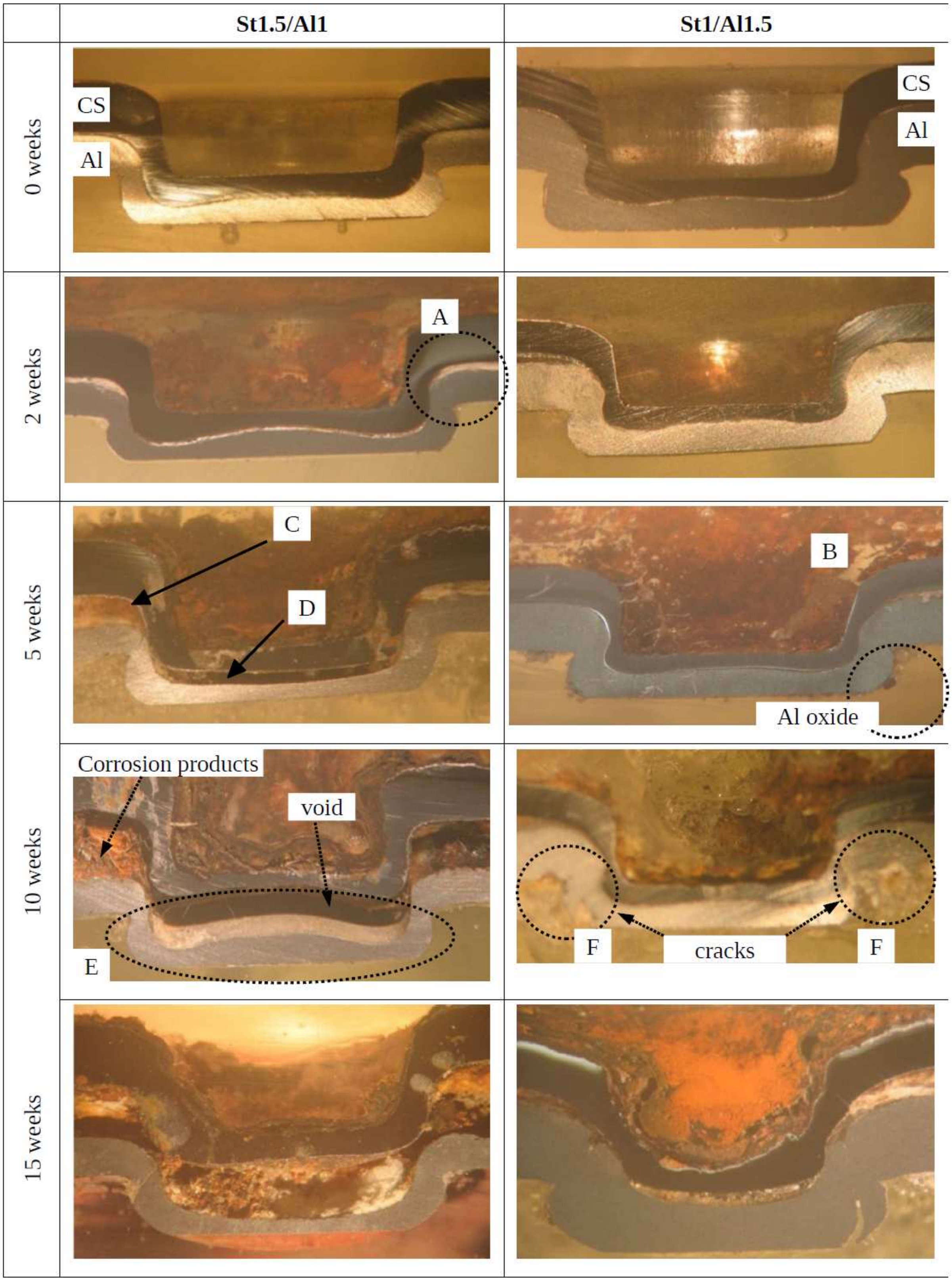


Figure 10: Cross sections of clinched joints at different ageing time. CS: Carbon steel; Al: Aluminium alloy. For letters from A to F refer to text.

At the same time, galvanic corrosion promotes aluminium sheet thinning. At high ageing times a combined unbuttoning-shear out failure mechanisms was observed. The former is due to reduced interlocking and the latter is activated by the low residual resistance of the aluminium at the button edge [29]. At the same time, galvanic corrosion promotes aluminium sheet thinning. At high ageing times a combined unbuttoning-shear out failure mechanisms was observed. The former is due to reduced interlocking and the latter is activated by the low residual resistance of the aluminium at the button edge [28].

This behaviour was not observed at medium ageing times in St1/Al1.5 samples where crevice corrosion phenomena took place only after the 5th week. In this case, as evidenced by point B in Figure 10, near the joint overlapping area there was the initial formation of aluminium oxides (with the characteristic whitish colour). Despite the St1.5/Al1 batch, the St1/Al1.5 batch presents the loss of contact and shear-out failure at the base button only after fifteen ageing weeks.

On the other hand, microcracks on the button may trigger corrosion phenomena as a consequence of stress corrosion cracking, induced by the internal stress states during the clinching process, as it is shown in Figure 10 (point F). In fact, the combined presence of a residual stress state around the clinched button and the critical environmental conditions, that here they operate, can lead to the premature propagation of cracks by stress corrosion cracking even in the absence of external mechanical stresses.

Since clinching is a localized cold forming process, symmetric compressive residual hoop stresses could extends outside up to a same distance with the button diameter [34]. This result was confirmed by Sjöström and Johansson for clinched joints produced with an open die [35].

Although it should be noted that these stress corrosion cracking phenomena have not still led to a significant reduction of the mechanical performance of the St1/Al1.5 joints over ageing time, as shown by the figure 9, they influence the interlocking interaction between sheets by promoting the detachment of the upper sheet from the lower one.

Failure Modes

Usually three basic modes of failure have been cited in the literature for loaded clinched joints [17][36] (figure 11).

The button pull-out failure mode (figure 11a) takes place when the separation of the upper and lower work-pieces occurs. This failure mechanisms is mainly due to minor geometric interlocking between the metal sheets caused by insufficient deformation in correspondence of the clinched button. The neck cracking failure mode (figure 11b) is usually attributed to an insufficient amount of the upper sheet material in the neck region. This can be due to a too small clearance of the tool diameter or a too deep depth of the mould die, which leads to an excess of elongation in the region of the neck joint, causing the formation of a cracks [24]. If the clinched joint have both a good undercut and adequate neck thickness a mixed failure mode can occur (figure 11c). In this case the combination of both the previous discussed failure mechanisms contribute to the mechanical instability of the joint.

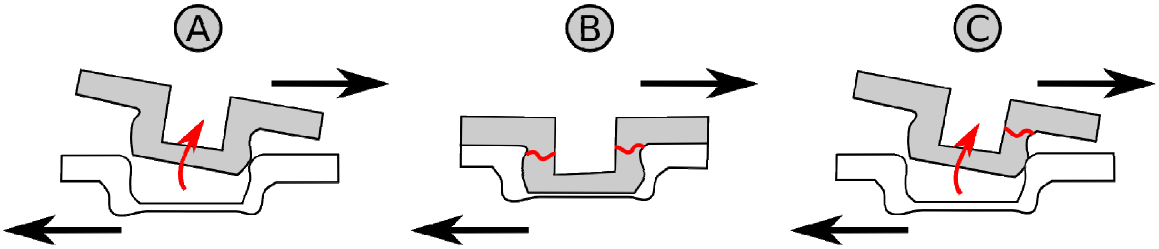


Figure 11: Scheme of failure mode: a) unbuttoning b) neck cracking c) mixed mode

Lee et al. [36] proposed two analytical models to estimate the failure strength for respectively neck cracking (F_N) and button pull-out (unbuttoning, F_B) failure mechanism:

$$F_N = \sigma_f \cdot A_N = \pi\left(2R_P t_N + t_N^2\right) \cdot \sigma_f \tag{1}$$

$$F_B = \pi\left(2R_P t_N + t_N^2\right) \cdot \sigma_y \cdot \left(\frac{1+\mu/\tan\alpha}{\mu/\tan\alpha}\right)\left[1-\left(\frac{t_N}{t_U+t_N}\right)\right]^{\mu/\tan\alpha} \tag{2}$$

Where R_P is the punch radius, t_N and t_U are respectively the neck and the undercut thickness, μ is the friction coefficient. α is the angle of the undercut steel/aluminium interface (geometrical parameter details of the clinched joints are reported in figure 12). σ_f is failure stress of the upper sheet and σ_y is average flow stress in the clinched region. The yield stress of the upper sheet was assumed as the average flow stress to consider the effect of hardening work caused by the clinching process [36].

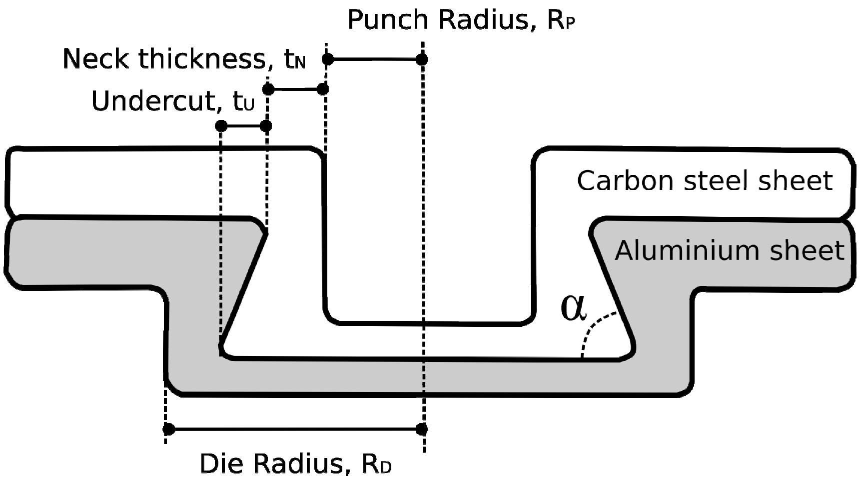


Figure 12: Geometrical parameters of the clinched joint

Starting from these assumption it is possible to describe, by a simplified approach, how the values of failure strength can vary for effect of the ageing in corrosive environment. The corrosion phenomena do not affect the carbon steel sheet thickness significantly thus it can be assumed that the neck cracking stress is not affected by ageing phenomena in present study. Therefore in the general relationship between neck cracking strength (F_N) and residual neck cracking strength after ageing (F_n^{aged}) C_N can be approximately equated to unity, $C_N \approx 1$,where C_N is a neck cracking corrosion induced coefficient.

$$F_N^{aged} = C_N \cdot F_N \qquad (3)$$

Instead on the overlapping area, crevice corrosion has occurred. The metal oxides (product of the redox reactions) precipitate on the interstices of the joint modifying the interlocking force and at the same time the undercut thickness. This implies that the unbuttoning stress should be related with the ageing time, according to a simplified relationship:

$$F_B^{aged} = C_B(t) \cdot F_N \qquad (4)$$

where $C_B(t)$, the unbuttoning corrosion coefficient ($C_B(t)<1$), is a time-dependent corrosion parameter that allows to take into account the relevant reduction of the unbuttoning resistance of the joint.

Furthermore, as previously discussed, at long ageing time, the advanced degradation state of the lower aluminium sheet favours the activation of a failure by shear-out. The force required to generate shear-out failure can be defined by [33]:

$$F_{SO} = \sigma_{YS} \cdot h \cdot s_{down} \tag{5}$$

Where σ_{YS} is the ultimate shear stress, h is the distance of the sheet edge from clinch button centre and s_{down} is the thickness of the lower aluminium plate (figure 2). In fact, due to dissolution phenomena on the aluminium sheet, a progressive reduction of h (and s_{down}, less relevant) can be observed. Consequently the shear-out strength of aged joint can be defined by following expression:

$$F_{SO}^{aged} = C_{SO}(t) \cdot F_{SO} \tag{6}$$

Where $C_{SO}(t)$ is a corrosion time-dependent coefficient related with the progressive reduction of the distance (h) between the sheet edge and the rivet induced by the galvanic corrosion of the anodic aluminium sheet during salt spray test.

Plotting the Eq. (3), (4) and (6) in a load versus time axis system, we can obtain a failure map for each batch, as reported in figure 10.

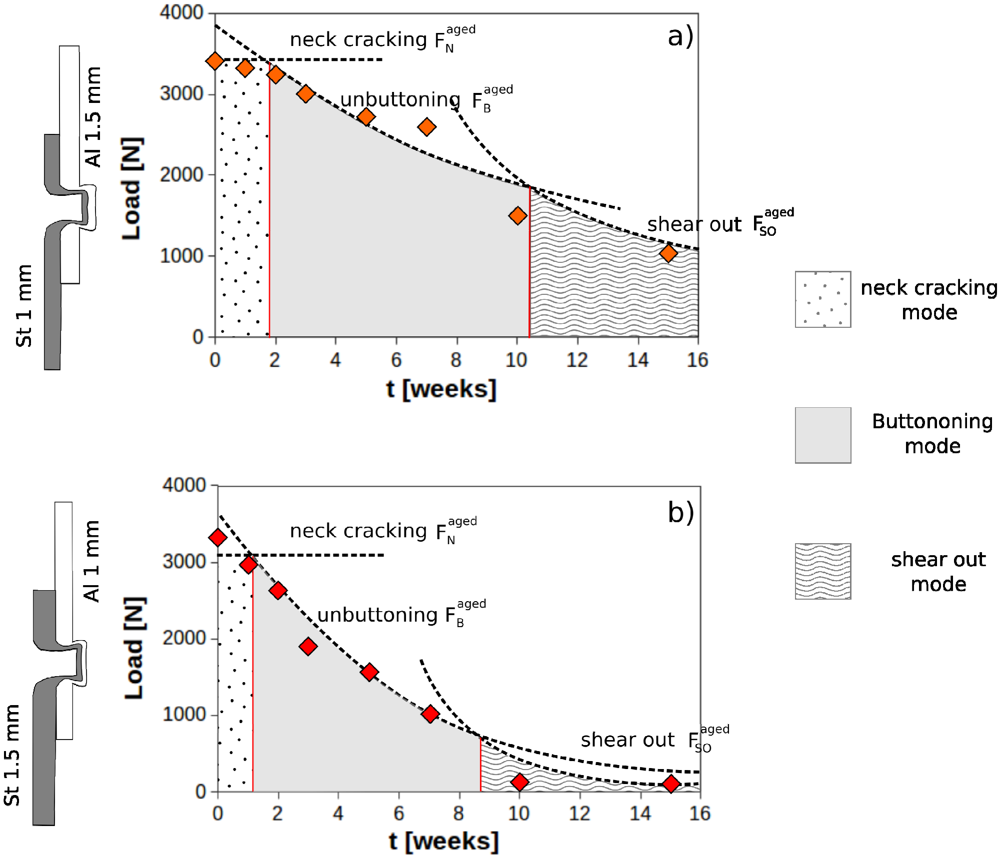


Figure 13: Failure map of a) St1/Al1.5 clinched joints b) St1.5/Al1 clinched joints

In table 2 the time-dependant corrosion coefficients were reported.

	St1/Al1.5	***St1.5/Al1***
C_N	1	1
C_B	$1.173*e^{-0.210*t}$	$1.075*e^{-0.073*t}$
C_{SO}	$7.565*e^{-0.438*t}$	$3.180*e^{-0.174*t}$

Table 2: Equation of time-dependent corrosion coefficients used to plot figure 13 (t expressed in weeks)

At low ageing time, the neck cracking is the dominant failure mechanism. At medium ageing time, the progressive reduction of the button strength induces the premature failure of the joints due to this failure mechanism.

At very long ageing time a shear-out failure mechanism was observed. However, in this last region it is evident that different failure mechanisms (unbuttoning and shear-out) have quite similar resistance limits, favouring mixed fracture mode of the samples.

The failure mechanisms, provided by this simplified theoretical model, are in line with those experimentally observed. The results evidence that increasing the ageing time in a corrosive environment the mechanical performances and the failure mechanisms are heavily influenced by the degradation of the aluminium work-piece. In particular the reduction of the interlocking force promotes unbuttoning phenomena of the joint. Only at long ageing time the drastic dissolution of the less noble aluminium sheet induces a premature fracture by shear out mechanism (or/and net-tension not described in this theoretical model).

This approach, with the failure map, does not allow to provide information on the effect of the stress distributions for the clinched joints, but still allows to have information on the mechanical behaviour of the joint and support the designer on how to consider the durability aspects in aggressive environmental conditions of dissimilar metal joints.

Conclusions

In this paper the ageing behaviour of metal-mixed clinched joints has been evaluated with the aim to evidence the relationship between the mechanical properties and corrosion phenomena.

The joints, aged in salt spray fog chamber, were characterised by means of single lap shear test. The results evidence that the mechanical strength is reduced at increasing ageing time. The galvanic coupling in the overlapping area between the less noble aluminium sheet and the more noble steel one has critical effects on the former metallic plate (aluminium alloy). The degradation of the aluminium foil leads to at medium ageing time unbuttoning failure mechanism. At long ageing time the large dissolution of the lower aluminium sheet induces a premature fracture by shear out and/or net-tension. These phenomena are significant for St1.5/Al1 samples, as for St1/Al1.5 samples acceptable mechanical properties have been observed until fifteen weeks of ageing. Finally a simplified theoretical model, allowing by means of failure maps, to explain the corrosion effect on the main failure mechanisms that occurred on the metal joints, has been proposed. Such failure maps, tailored for the employed materials and thicknesses, can be an appreciable and potential tool for the design of clinched joint at long ageing time.

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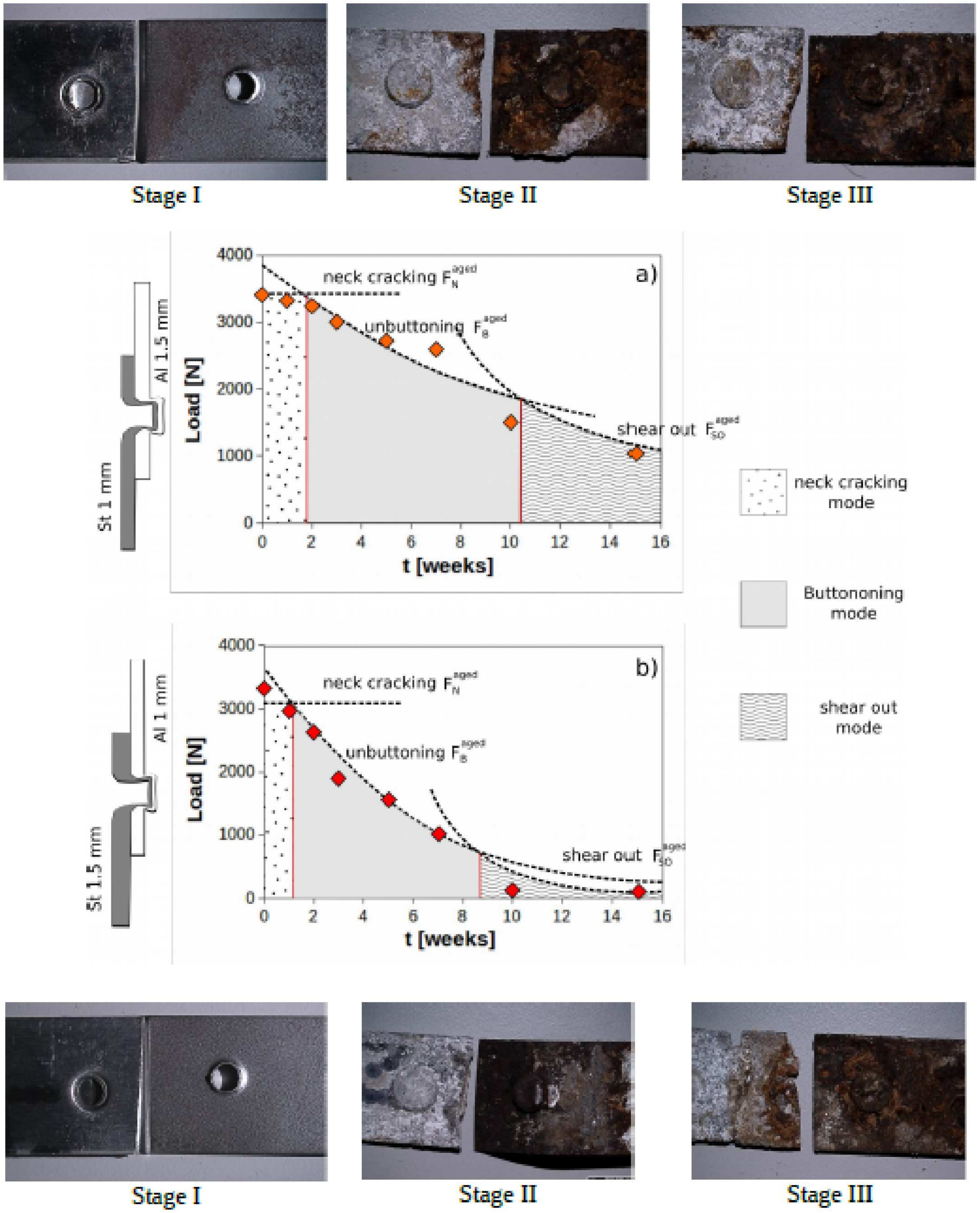

Graphical abstract

Highlights

- Clinched aluminium-carbon steel joints degrade due to ageing in salt spray fog test.
- Mechanical performances of the joints decrease significantly at increasing ageing time.
- Corrosion degradation of sheets is related to metal joint cofiguration.
- A simplified theoretical model was proposed efficiently to interpret the corrosion effect.