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ORIGINAL ARTICLE

# Effect of a nano-structured zirconium coating on the mechanical performance of clinched steel–aluminum joints

João Vinícius de Souza Vares[1] · Halston José Mozetic[1] · Lírio Schaeffer[1]

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## Abstract

This study investigates the effect of a nano-structured zirconium-based conversion coating on the mechanical performance and corrosion behavior of clinched joints between SAE1006 steel and AA3004 aluminum sheets. Clinching is a mechanical joining process based on localized plastic deformation that enables the joining of dissimilar sheet metals without additional elements or thermal input, making it attractive for lightweight structural applications in the automotive and metalworking industries. In this work, sheets with and without zirconium-based nano-ceramic coating were joined by clinching and comparatively evaluated. The joints were characterized through force–displacement analysis during the joining process, shear strength testing, microhardness measurements, and microstructural analysis using optical microscopy, scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and atomic force microscopy (AFM). Accelerated corrosion tests in a saturated humidity chamber were also performed to qualitatively assess corrosion resistance. The results showed that the nano-structured coating significantly modified the surface topography of the sheets, increasing surface roughness and altering the interfacial conditions established during clinching. As a consequence, the coated joints exhibited an average increase of approximately 68% in shear strength compared with uncoated joints, without requiring higher joining forces. In addition, the zirconium-based coating demonstrated effective corrosion protection under accelerated humidity exposure. These findings suggest that nano-structured zirconium conversion coatings can improve both the mechanical performance and corrosion resistance of clinched joints. The results also indicate that surface modifications introduced by the coating may contribute to enhanced joint performance without requiring changes to the clinching process itself.

**Keywords** Clinching · Dissimilar metal joining · Zirconium conversion coating · Nano-structured coating · Steel–aluminum joints · Shear strength

## 1 Introduction

In modern manufacturing industries, the development of efficient and reliable methods for joining metallic components is essential for the production of lightweight and structurally efficient assemblies. This demand is particularly relevant in the automotive sector, where weight reduction, energy efficiency, and environmental concerns have intensified the adoption of multi-material design strategies. Among the possible material combinations, steel and aluminum have attracted special attention because they allow the integration of the high strength and low cost of steel with the low density and good corrosion resistance of aluminum, contributing to improved structural efficiency and reduced vehicle mass [1–3].

Despite these advantages, joining dissimilar materials remains a major technological challenge. Conventional fusion-based joining processes may be unsuitable for steel–aluminum combinations because of the formation of brittle intermetallic compounds, differences in thermal expansion, and the distinct physical and metallurgical characteristics of the materials involved. In addition, thermal joining routes may introduce microstructural changes that are undesirable for lightweight sheet structures. For this reason, alternative joining technologies capable of producing reliable joints without significant thermal effects have become increasingly important [4–6].

✉ João Vinícius de Souza Vares
joaoviniciusvares@gmail.com; joao.vares@ufrgs.br

[1] Metal Forming Innovation Center (CBCM), Federal University of Rio Grande do Sul, Porto Alegre, Brazil

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Among these alternatives, clinching has emerged as a promising mechanical joining process for sheet metals. The process is based on localized plastic deformation, in which a punch and die are used to create a mechanical interlock between overlapping sheets without the need for additional fasteners, filler materials, or pre-drilled holes. Clinching offers several advantages, including low energy consumption, short cycle times, ease of automation, and the ability to join dissimilar materials, which has supported its growing application in automotive, appliance, and lightweight structural manufacturing [7–10].

As the industrial use of clinching has expanded, considerable research efforts have been directed toward improving the mechanical performance and reliability of clinched joints. Recent studies have investigated alternative die geometries, die-less clinching approaches, adhesive-assisted clinching, and the use of auxiliary sheets to increase joint strength and structural integrity [11, 12]. Although these approaches have demonstrated promising results, many of them require modifications to tooling systems, additional materials, or changes in manufacturing procedures, which may increase process complexity and production costs.

An alternative strategy consists of modifying the surface condition of the sheets prior to joining. Surface engineering treatments can influence the interaction between contacting materials during deformation processes and may affect the final performance of mechanically joined assemblies. Among the available surface treatments, zirconium-based conversion coatings have received considerable attention as environmentally friendly alternatives to conventional chromate-based systems. These coatings form nanometric ceramic layers on metallic substrates and are widely recognized for providing corrosion protection while complying with increasingly restrictive environmental regulations [13–16].

In addition to their protective function, zirconium-based nano-structured coatings significantly modify surface topography and roughness characteristics. Previous studies have shown that these coatings can generate heterogeneous nanometric surface features and alter the morphology of both steel and aluminum substrates [17–21]. Such modifications may influence the interfacial conditions established during forming-based joining processes and, consequently, affect the mechanical behavior of the resulting joints. Therefore, combining a surface treatment of this type with clinching may represent a simple and attractive strategy for improving joint performance without requiring changes to the joining process itself.

Although zirconium-based conversion coatings have been extensively investigated with respect to corrosion protection and surface modification of metallic substrates, their influence on the mechanical performance of clinched joints remains largely unexplored. In particular, limited information is available concerning the effect of coating-induced surface modifications on clinched steel–aluminum assemblies. Moreover, while the corrosion-protection role of zirconium-based coatings is already well established in the literature, their contribution to the behavior of mechanically joined dissimilar sheets has not been sufficiently clarified. In this context, corrosion assessment in the present work is treated as a complementary qualitative analysis, whereas the main focus is placed on the mechanical and interfacial behavior of the clinched joints.

Therefore, the present study investigates the effect of a nano-structured zirconium-based conversion coating on the performance of clinched joints produced using SAE1006 steel and AA3004 aluminum sheets. The influence of the coating was evaluated through force–displacement analysis during clinching, shear strength testing, microhardness measurements, optical microscopy, scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and atomic force microscopy (AFM). In addition, accelerated corrosion tests were conducted to qualitatively assess the protective behavior of the coating. The objective is to determine whether coating-induced modifications in surface characteristics can influence the mechanical performance and durability of clinched joints without requiring changes to the clinching process itself.

## 2 Materials and methods

### 2.1 Clinched joints

Two distinct materials were selected for the experimental procedures: SAE1006 carbon steel with a thickness of 0.6 mm and AA3004 aluminum with a thickness of 1 mm. SAE1006 steel was chosen for its ductility and good weldability, while the AA3004 alloy, which contains manganese as the main alloying element, is known for its mechanical properties and corrosion resistance [22]. Test specimens measuring 100 × 20 mm were fabricated from these sheets. A total of 60 specimens were produced: 30 of SAE1006 steel and 30 of AA3004 aluminum. The sheets were cut on a guillotine to form the pairs to be joined. Half of the specimens were subjected to a nano-ceramic conversion coating process to analyze the influence of this treatment on the joint properties. A cylindrical joint element without auxiliary material was adopted for clinching, given its versatility and extensive use in the industry in general, as schematically represented in Fig. 1 [23–26].

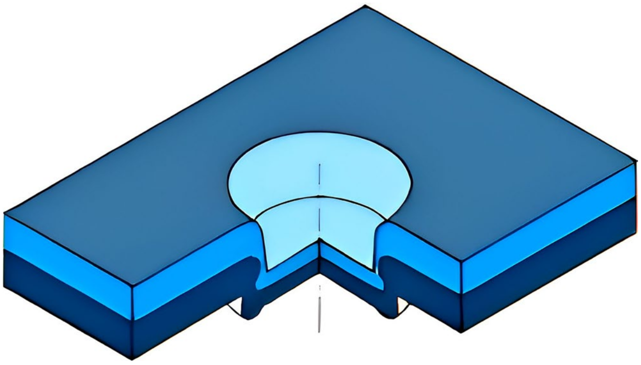

**Fig. 1** Schematic representation of the tool configuration used for cylindrical clinching joints without auxiliary elements, illustrating the die geometry responsible for forming the mechanical interlocking region

## 2.2 Nano-structured ceramic coating

Commercial phosphate-free conversion solutions based on hexafluorozirconic acid (H2ZrF6) were used to produce the nano-structured ceramic coating [17]. Part of the metal sheets was subjected to a sequence of operations, starting with washing to remove excess oil, alkaline degreasing with a solution of sodium salts and anionic surfactants at 65 °C for 15 min, washing with deionized water, water break test, hot air drying, immersion in the conversion solution for 50 s, washing with deionized water, and hot air drying.

## 2.3 Characterization

The characterization of clinched joints was conducted through mechanical tests and microstructural analyses to understand the impact of the nano-structured ceramic coating on the properties of the joints.

### 2.3.1 Shear by tension tests

The shear by tension tests were conducted according to the ABNT NBR ISO 6891-1 standard using the EMIC DL60000 universal testing machine (60t). After clinching the sheets, the tests evaluated the mechanical strength of the joints, which failed by shearing when the locking region yielded [27].

### 2.3.2 Microhardness analysis

Microhardness analyses were performed with a QATM QNESS 60 A/A+EVO microhardness tester using a Vickers penetrator (100 gf) according to ASTM E92-17. Cross-sectional cuts in the center of the joints allowed measuring the microhardness in different zones with three indentations per point.

### 2.3.3 Microstructural analysis

Microstructural analyses involved cutting, embedding, grinding, and polishing the samples, revealed with 2% Nital, and analyzed with a LEICA DMi8A optical microscope. Atomic force microscope BRUKER DIMENSION ICON and scanning electron microscope FEI INSPECT F50 with EDS were used to evaluate the topography and the presence of zirconium oxide on the metal surfaces.

### 2.3.4 Corrosion tests

Accelerated corrosion tests were conducted to evaluate the surface degradation behavior of SAE 1006 carbon steel in three distinct conditions: (i) coated with zirconium-based nano-structured ceramic, (ii) uncoated as-received, and (iii) uncoated but chemically cleaned. Five samples were tested per condition. These tests aimed to observe the protective effect of the ceramic coating under aggressive environmental conditions, especially when combined with the clinching process.

The methodology was based on ABNT NBR 8095:2015 [28], using a saturated humid chamber set to 40 °C and 100% relative humidity, simulating an environment conducive to atmospheric corrosion. The test duration was 168 h.

Due to the specific scope of this study, centered on evaluating the mechanical and structural performance of clinched joints involving coated and uncoated substrates, corrosion resistance was assessed through a comparative qualitative analysis.

A standardized corrosion grading scale was applied based on visual inspection of surface degradation patterns, as defined in Table 1. This approach, commonly adopted in accelerated corrosion studies, is consistent with prior research demonstrating the practical effectiveness of zirconium conversion coatings in delaying the onset and propagation of corrosion [29–31].

After 168 h of exposure, photographic records were taken to document the surface condition of each sample. These images were used to qualitatively assess the extent and pattern of corrosion, based on the standardized grading scale. Representative examples are presented in Sect. 3.

**Table 1** Criteria for assigning corrosion grades indicating their intensity

| Grade | Description |
|---|---|
| 0 | Perfect, no corrosion |
| 1 | Localized spots |
| 2 | Generalized spots |
| 3 | Localized areas |
| 4 | Partial: spots and areas |
| 5 | Total corrosion |

Zirconium-based conversion coatings are widely recognized for their ability to inhibit corrosion initiation and propagation on steel and aluminum alloys, even under aggressive conditions [20, 21, 30, 31].

## 3 Results and discussion

This section presents the experimental results obtained from the clinching process and the corresponding mechanical, microstructural, and corrosion analyses performed on coated and uncoated sheet specimens. The results are discussed in terms of process behavior, joint mechanical performance, surface characteristics, and corrosion resistance, providing a comprehensive evaluation of the influence of the nano-structured zirconium coating on the performance of the clinched joints.

### 3.1 Clinching

The specimens were joined by clinching according to the experimental configurations.

Figure 2 presents a schematic representation of the clinching process, indicating the force (F) exerted by the punch and the displacement (d) made during the process [32].

Figure 3 illustrates the force (F) versus displacement (d) relationship during clinching, highlighting the punch advance and retreat stages. Figure 3A represents the samples without coating, while Fig. 3B shows the samples with nano-ceramic coating.

For the steel-steel sheet joints, the configurations with and without the nano-ceramic coating presented similar displacements and shear resistive forces around 13.5 kN. In the aluminum-aluminum configuration, resistive forces varied between 2.89 and 3.15 kN. For the steel-aluminum joint, displacements were also similar, with forces around 1.4 kN.

The presence of the nano-structured ceramic coating did not cause significant changes in the joining process, with processing forces compatible with the findings of Kupfer et al. [33], Nourani et al. [34], and Sarmento [35]. The similarity between the force–displacement curves obtained for coated and uncoated sheets indicates that the coating did not significantly influence the overall forming behavior during clinching.

The primary objective of applying the zirconium-based nano-structured coating was not to modify the forming stage of the clinching process itself, but rather to investigate whether coating-induced changes in surface characteristics could influence the final mechanical performance of the joints. Because the conversion coating forms a nanometric layer on the sheet surface, substantial changes in material flow, punch penetration, or forming forces were not expected. Therefore, the similarity observed in the force–displacement curves indicates that the coating did not significantly affect the clinching operation. The initial hypothesis of this study was that modifications in surface

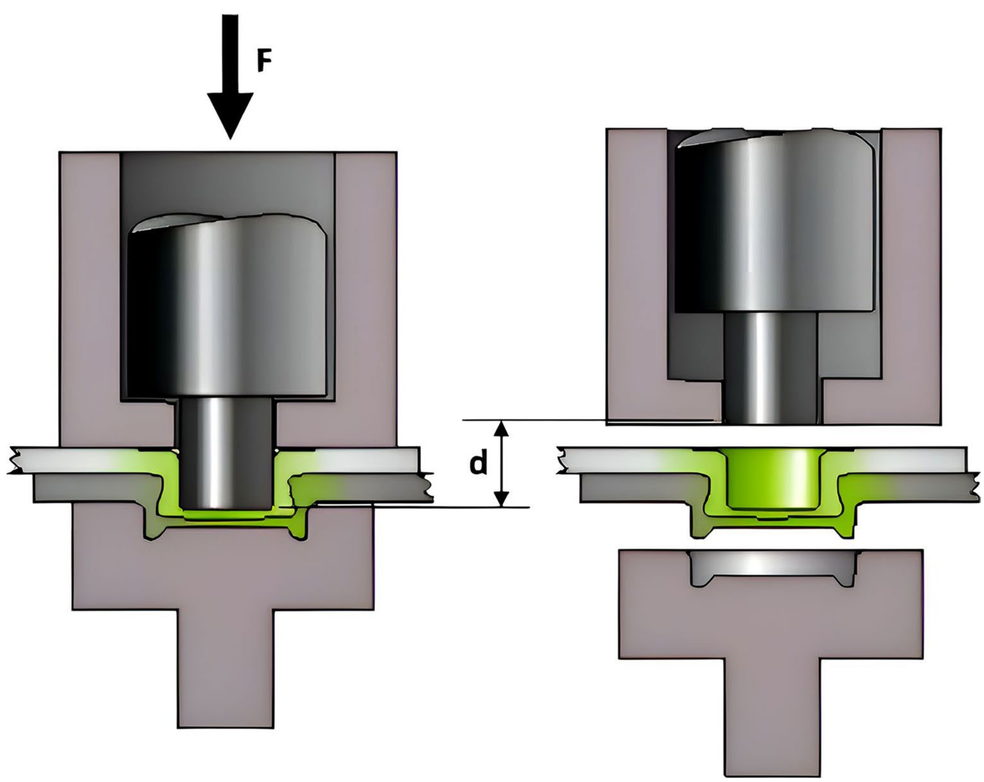


**Fig. 2** Schematic illustration of the clinching process indicating the punch advance and retreat stages and the formation of the mechanical interlocking region between the sheets

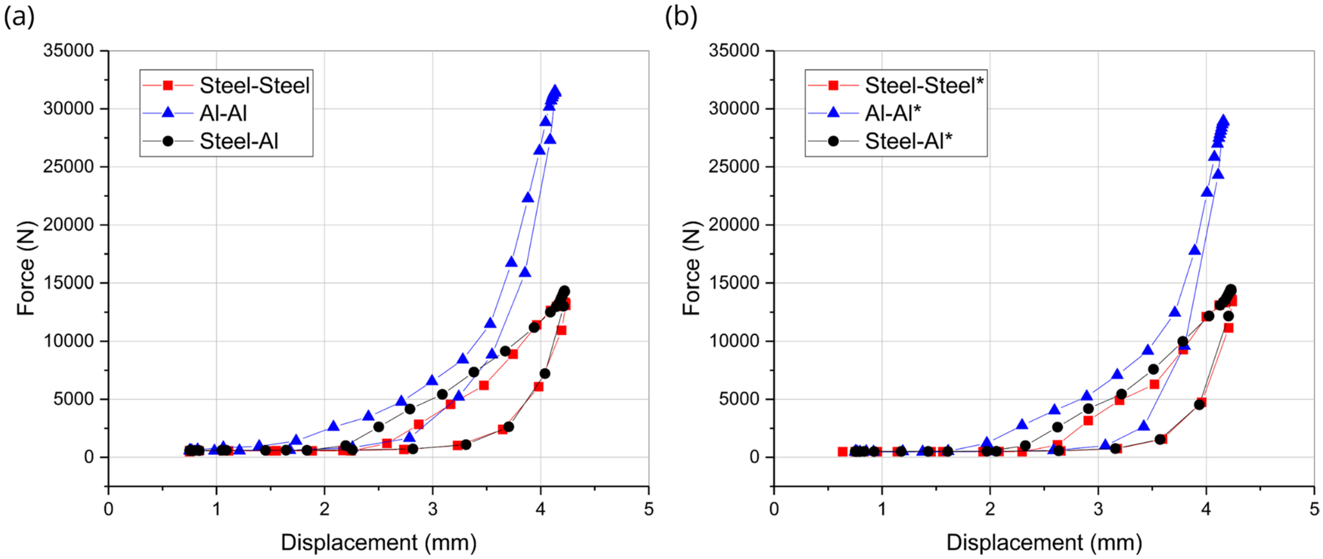


**Fig. 3** Force–displacement curves obtained during the clinching process: (**a**) uncoated sheets and (**b**) sheets with nano-ceramic zirconium coating, showing the punch advance and retreat stages during joint formation

topography and roughness promoted by the coating could alter the interfacial conditions between the sheets and contribute to improved joint performance. This hypothesis is further examined through the mechanical and surface characterization results presented in the following sections.

## 3.2 Shear strength test

After the clinching process, the joined specimens were subjected to shear tensile tests to evaluate the mechanical strength of the joints. This test allows the assessment of the load-bearing capacity of the mechanical interlocking region formed during clinching. Figure 4 presents a schematic representation of the specimen configuration used during the shear test [36].

The mechanical behavior of the joints during the shear tensile test is presented in Fig. 5 for the steel–steel, aluminum–aluminum, and steel–aluminum configurations. For each material configuration and surface condition, three independent shear tensile tests were performed ($n = 3$). Therefore, each curve shown in Fig. 5 corresponds to one individual test (replicate). This representation was adopted to directly visualize the repeatability of the mechanical response and the characteristic shape of the force–displacement curves.

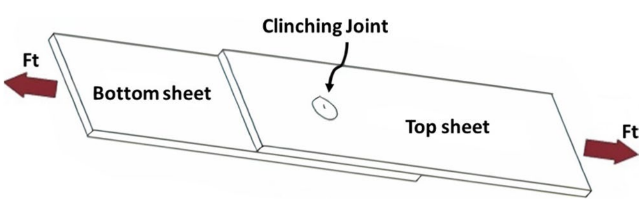


**Fig. 4** Shear of the joint in a tension test

Table 2 summarizes the maximum shear force ( $F_{max}$) results obtained for each material configuration and surface condition. The data confirm that, although the clinching process exhibits inherent variability (reflected in the standard deviation and coefficients of variation), the improvement in mechanical strength promoted by the nano-ceramic coating is consistent across all tests.

Data summarized in Table 2 indicate a systematic increase in maximum shear force for all coated configurations. Although the clinching process inherently exhibits some variability, particularly for the uncoated aluminum joints (CV = 22%), the same tendency was observed in all experimental replicates. The increase in shear strength may be associated with the surface modifications identified by AFM analysis. The higher roughness produced by the nanometric zirconium layer likely altered the interfacial conditions established during clinching and contributed to a more effective transmission of load through the joint. Since the force–displacement curves obtained during clinching remained essentially unchanged, the observed improvement appears to be more closely related to surface effects than to modifications in the overall forming behavior.

Although some dispersion is observed among the independent replicates, the overall trend was consistent for all material configurations. In each case, the coated joints exhibited higher maximum shear force than the corresponding uncoated joints. The differences among curves obtained under the same nominal condition are likely associated with the inherent variability of the clinching process, which is influenced by local material flow, minor variations in sheet positioning, deformation of the interlocking region, and the failure path developed during shear loading. Such variability is expected in mechanical

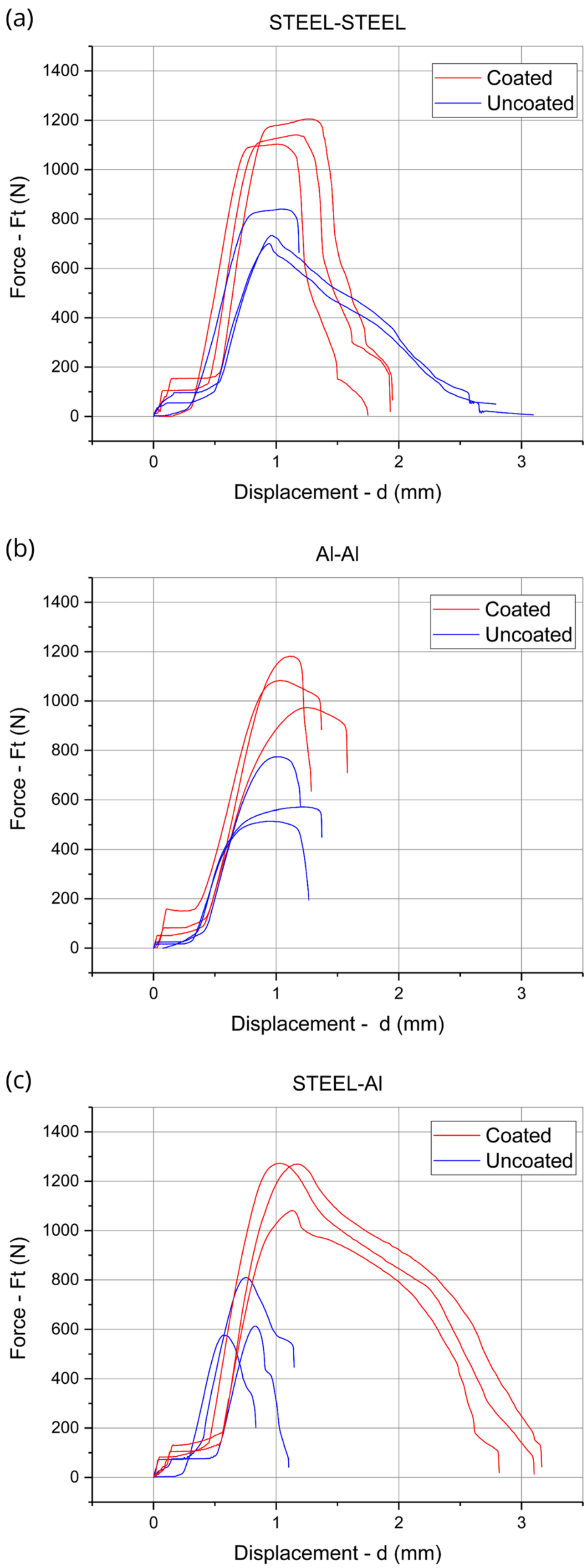


**Fig. 5** Force–displacement curves obtained from shear tensile tests of clinched joints: (**a**) steel–steel, (**b**) aluminum–aluminum, and (**c**) steel–aluminum configurations. For each material configuration and surface condition, three independent replicates were tested ($n=3$). Red curves correspond to coated sheets, and blue curves correspond to uncoated sheets

joining processes based on localized plastic deformation. Nevertheless, the repeated increase in maximum shear force observed for the coated condition across all experimental sets strongly suggests that the coating contributed positively to the mechanical performance of the clinched joints.

Overall, the results indicate that the nano-structured zirconium coating provided an average increase of approximately 68% in the shear strength of the clinched joints. This improvement may be associated with the surface modifications induced by the nanometric conversion coating, which increased surface roughness and altered the interfacial conditions established during clinching. The higher roughness may have promoted more effective interaction between the contacting surfaces and improved load transfer across the joint, contributing to the observed increase in shear strength. These findings are consistent with previous studies highlighting the importance of surface conditions, interfacial interaction, and material flow in determining the mechanical performance of clinched joints [11, 37].

### 3.3 Microhardness test

Microhardness measurements were taken at points of the cross-section of the clinched sheets (Fig. 6(a)).

The microhardness values obtained are presented in graphs for each joint sheet (lower and upper) in the conditions with and without the nano-ceramic coating. In the microhardness profiles of the steel-steel and aluminum-aluminum joints (Figs. 6(b) and 6(c)), a reduction in microhardness values was observed at points 4 and 5, respectively, contrasting with the expected behavior of an increase due to work hardening caused by intense plastic deformation in the interlocking zone. This discrepant behavior can be explained by the phenomenon of reverse material flow, where, during the clinching process, the material near the punch curvature radius is displaced from the base toward the neck, resulting in localized stress redistribution and lower hardening density in specific points. This reverse flow, an intrinsic characteristic of clinching, is detailed by Zhang and Chen [37], who highlight how material dynamics in the interlocking zone can create areas with reduced compaction and variations in microhardness. Additionally, the interaction between material flow and mechanical interlocking mechanisms can cause heterogeneous deformations in the upper sheets, as described by Abe et al. [38], especially in processes involving materials with different mechanical responses, such as steel and

**Table 2** Summary of maximum shear force ($F_{max}$) results for clinched joints ($n$=3 per condition)

| Configuration | Condition | $n$ | Fmax (Mean ± SD) [$N$] | CV (%) | Min–Max ($N$) |
|---|---|---|---|---|---|
| Steel–Steel | Uncoated | 3 | 758.1 ± 73.1 | 9.6 | 700.4–840.3 |
| Steel–Steel | Coated | 3 | 1149.5 ± 51.9 | 4.5 | 1102.9–1205.4 |
| Aluminum–Aluminum | Uncoated | 3 | 619.6 ± 136.6 | 22.0 | 514.0–773.8 |
| Aluminum–Aluminum | Coated | 3 | 1079.3 ± 103.6 | 9.6 | 974.0–1181.2 |
| Steel–Aluminum | Uncoated | 3 | 666.7 ± 125.3 | 18.8 | 577.1–809.8 |
| Steel–Aluminum | Coated | 3 | 1207.9 ± 109.6 | 9.1 | 1081.4–1272.6 |

aluminum. This observed behavior also aligns with analyses by Groche et al. [39], who emphasize the influence of geometric factors and the redistribution of residual stresses in the formation of clinched joints.

The nano-ceramic coating did not appear to substantially influence the microhardness profiles of the evaluated sheets (Fig. 6(d)), and similar hardness distributions were observed for coated and uncoated conditions.

### 3.4 Microstructural analysis

Atomic force microscopy (AFM) analysis provided detailed information on the surface topography. AFM measurements were performed over an area of 30 µm × 30 µm for each sample. Figure 7(a) shows the surface of an uncoated steel sample,

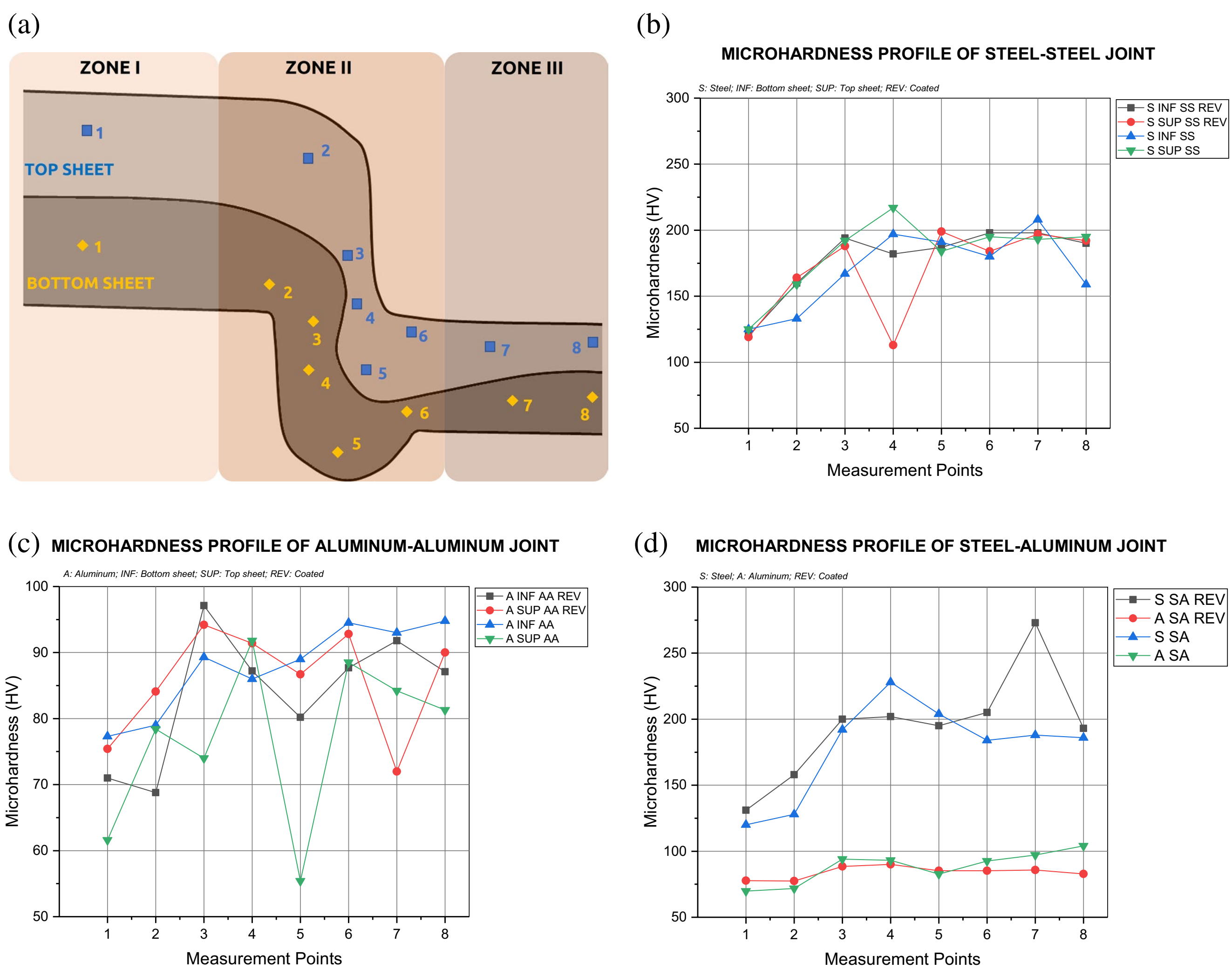


**Fig. 6** (**a**) Cross-sections of clinched sheets for microhardness analysis; Microhardness profile of the cross-sections of clinched sheets: (**b**) steel; (**c**) aluminum; (**d**) steel-aluminum

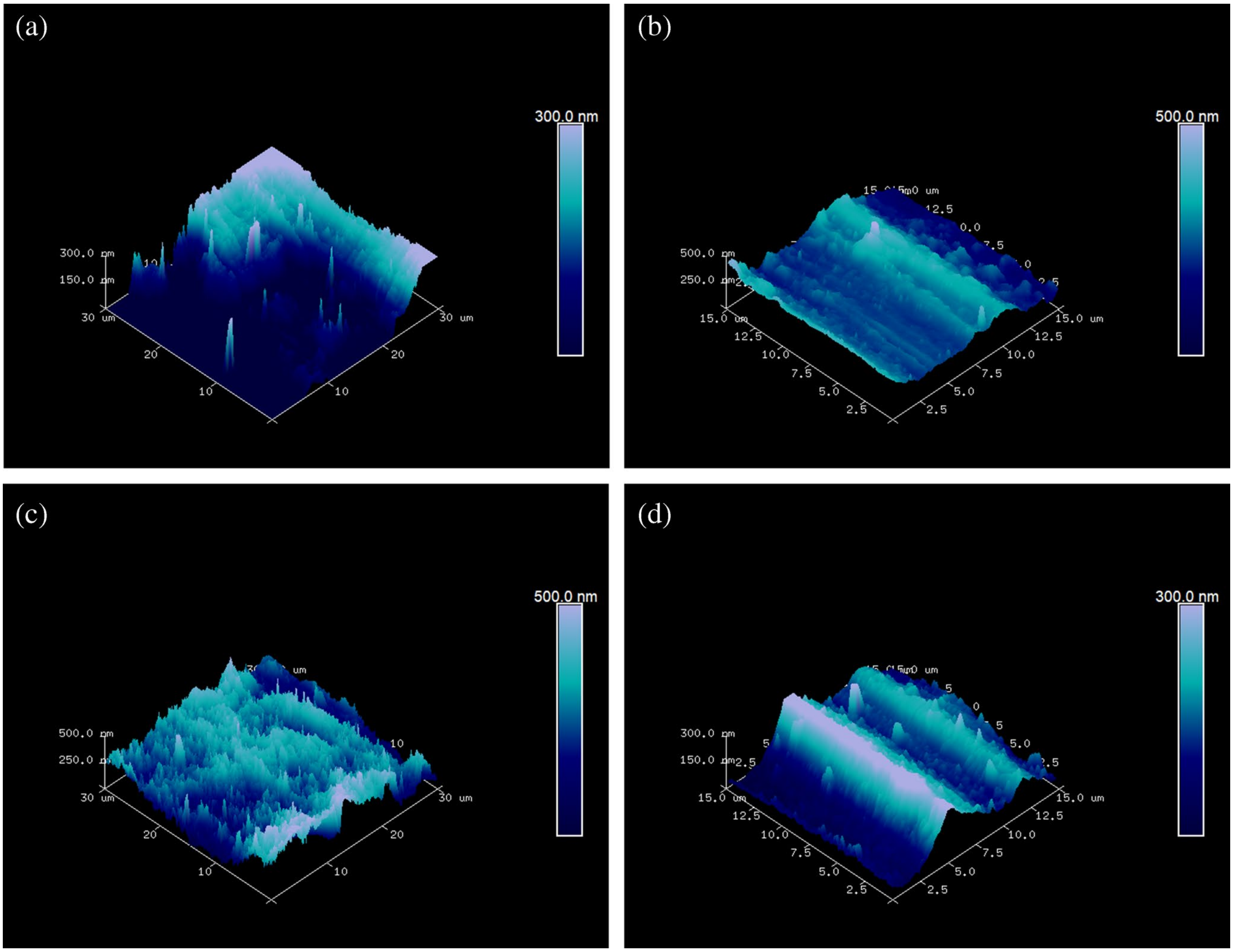


**Fig. 7** AFM topography of metal sheets: (**a**) uncoated steel; (**b**) uncoated aluminum; (**c**) coated steel; (**d**) coated aluminum. Color scales correspond to the height variation measured in each sample

displaying roughness and possible scratches indicative of previous abrasive processes. The surface exhibits an average roughness (Ra) of 30.941 nm and a peak-to-valley roughness (Rz) of 164.914 nm. The surface of an uncoated aluminum sample (Fig. 7(b)) shows similar characteristics to the steel sample, including oxidation areas. The average roughness (Ra) was 29.570 nm, and the peak-to-valley roughness (Rz) was 61.198 nm. For the steel sample with a hexafluorozirconic acid-based nano-ceramic coating (Fig. 7(c)), the micrograph reveals significant variations in topography with irregular grooves and elevations. The average roughness (Ra) was 88.156 nm, and the peak-to-valley roughness (Rz) was 277.644 nm, indicating a considerable increase in surface roughness compared to the uncoated condition. The micrograph of the surface of an aluminum sample with nano-ceramic coating (Fig. 7(d)) also presents significant alterations in topography compared to its natural condition. The average roughness (Ra) was 106.689 nm, and the peak-to-valley roughness (Rz) was 221.077 nm.

These changes in roughness and topography may influence the functional behavior of the surfaces, particularly regarding interfacial interaction and mechanical anchoring during joining processes.

The increase in shear strength observed for the coated joints may be related to the surface modifications introduced by the nano-structured coating. AFM analysis revealed substantial increases in surface roughness for both steel and aluminum substrates, indicating a significant alteration of the surface topography. Such modifications may have influenced the contact conditions between the sheets during clinching and contributed to the higher load-bearing capacity observed during mechanical testing. However, because geometric parameters of the interlocking region were not quantified in the present study, the specific mechanisms responsible for the strength increase cannot be established conclusively. Therefore, the relationship proposed here should be interpreted as a plausible explanation supported by the experimental observations rather than as direct evidence of a specific strengthening mechanism. Nevertheless, the results are consistent with the higher maximum loads measured for the coated joints and with observations reported in previous studies [40, 41].

Scanning electron microscopy (SEM) and EDS analyses allowed evaluating the morphology and composition of the hexafluorozirconic acid coating. The surface of a coated steel sample with zirconium particles identified in the EDS spectrum can be seen in Fig. 8(a), aligning with the works of Droniou et al. [42] and Testa [43].

The surface of the aluminum sheet with nano-ceramic coating (Fig. 8(b)) was also investigated, identifying the presence of Zr characteristic peaks by the EDS spectrum and the particles that make up the coating, consistent with the results obtained by Santa Coloma et al. [18] and Cerezo et al. [17].

SEM/EDS analyses complemented AFM observations, identifying the presence of zirconium on coated surfaces, highlighting the changes caused by the nano-ceramic coating compared to uncoated substrates.

### 3.5 Performance in corrosion tests

The results of the corrosion tests conducted in the saturated humid chamber (168 h at 40 °C) are shown in Fig. 9, representing the evolution of corrosion grade for the three evaluated conditions: (i) coated with zirconium-based nano-structured ceramic, (ii) uncoated as-received, and (iii) uncoated but chemically cleaned.

Five samples were tested per condition. The coated specimens maintained corrosion grade 0 throughout the initial 120 h, with a minor progression to grade 1 observed only at the end of the 168-hour exposure. In contrast, both uncoated conditions exhibited significantly more aggressive degradation: the as-received samples reached corrosion grade 4 after 168 h, while the chemically cleaned ones followed a similar or slightly worse trend. This behavior indicates that the chemical cleaning process, by removing surface oils and residues, exposed the bare metal to corrosion and increased its susceptibility compared to the as-received condition.

These results suggest that the zirconium-based coating provided effective protection against corrosion initiation and propagation under the accelerated humidity conditions employed in this study.

This performance is consistent with literature findings, which associate zirconium conversion coatings with enhanced surface passivation, suppression of localized attack, and formation of dense, homogeneous protective layers [21, 41].

The visual inspection of the samples after 168 h reinforces the comparative qualitative analysis shown in Fig. 9. Representative images are presented in Fig. 10.

It is evident that the coated sample exhibited only minor and localized signs of oxidation (corrosion grade 1), whereas both uncoated conditions displayed extensive rust coverage and severe surface degradation, consistent with corrosion grade 4. These visual findings confirm the superior corrosion protection afforded by the zirconium-based nano-structured coating [29–31].

## 4 Conclusions

This study investigated the influence of a nano-structured zirconium-based conversion coating on the performance of clinched joints between SAE1006 steel and AA3004 aluminum sheets. The experimental results demonstrated that the combination of surface treatment and mechanical joining can significantly influence joint behavior and durability.

The application of the nano-structured ceramic coating resulted in a substantial improvement in the mechanical strength of the clinched joints. The shear tensile tests showed increases of approximately 51% for steel–steel joints, 74% for aluminum–aluminum joints, and 81% for steel–aluminum joints when compared with uncoated conditions. On average, the coating promoted an increase of about 68% in joint shear strength.

Surface characterization revealed that the nano-ceramic coating significantly modified the topography of the metal sheets. Atomic force microscopy indicated increases of approximately 185% in the arithmetic mean roughness (Ra) for steel and 260% for aluminum. These surface modifications are believed to have influenced the interfacial conditions established during clinching and may have contributed to the observed improvement in joint strength.

In addition, the presence of the coating did not significantly affect the joining forces required during clinching, indicating compatibility with the existing manufacturing process without the need for modifications in tooling or equipment. Accelerated corrosion tests also confirmed the protective effect of the zirconium-based coating, which effectively delayed the onset and propagation of corrosion under humid exposure conditions.

Overall, the results obtained under the experimental conditions investigated in this study indicate that nano-structured zirconium conversion coatings have the potential to improve both the mechanical performance and corrosion resistance of clinched joints without significantly affecting the clinching process itself. These findings suggest that surface engineering treatments based on zirconium conversion coatings may represent a promising strategy for enhancing the reliability of joints between dissimilar metallic sheets in lightweight manufacturing applications.

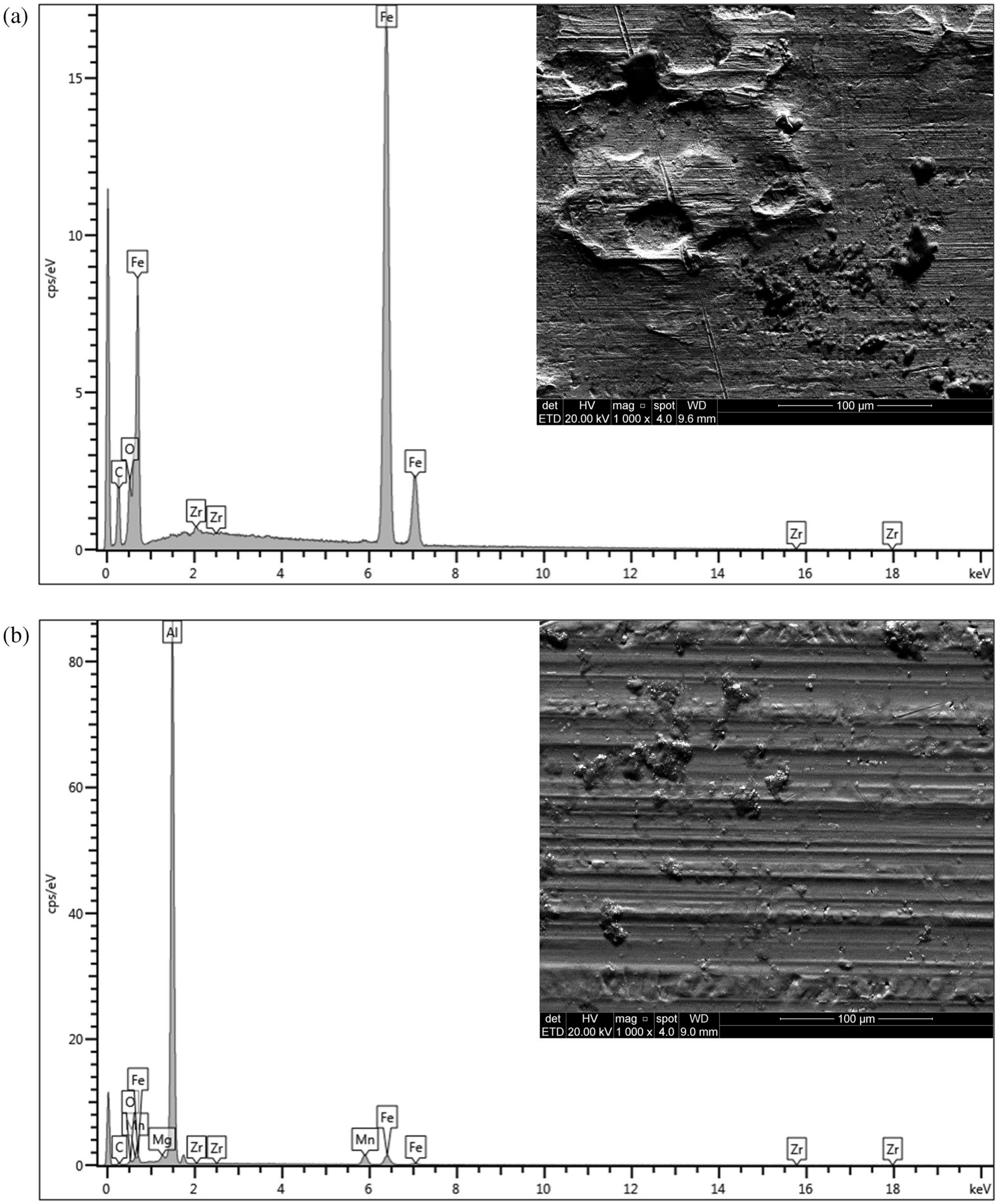


**Fig. 8** Scanning electron microscopy and EDS spectrum for (**a**) steel and (**b**) aluminum sheets, both coated with zirconium-based nano-ceramic

**Fig. 9** Evolution of corrosion grade over exposure time in a humid chamber for coated steel samples, uncoated as-received samples, and uncoated previously cleaned samples

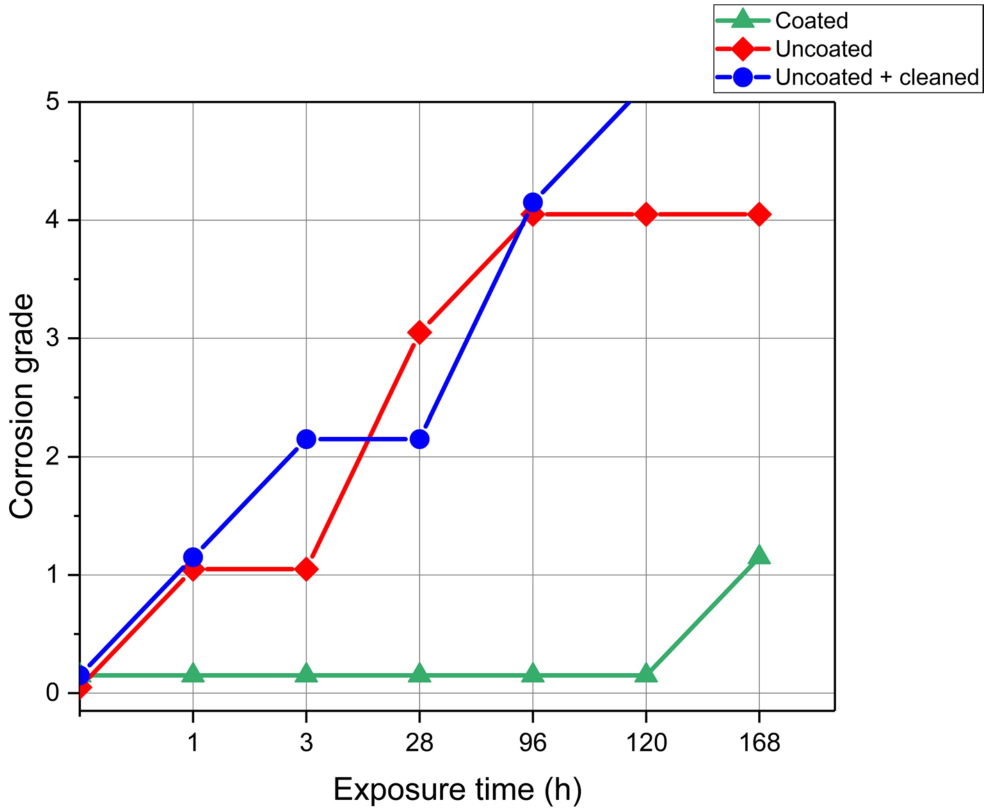



**Fig. 10** Representative surface images of the three test conditions after 168 h of exposure in the saturated humid chamber

Although the results demonstrated a clear improvement in joint performance for the coated condition, the present investigation was limited to the material combinations and experimental conditions evaluated. In addition, geometric parameters of the interlocking region were not measured, preventing a more detailed assessment of the mechanisms responsible for the increase in shear strength. Future studies including quantitative characterization of interlock geometry and larger experimental datasets may contribute to a more comprehensive understanding of the relationship between surface condition and joint performance.

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**Data availability** The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Competing interest** The authors declare that they have no conflict of interest.



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