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Corrosion behavior and characteristics of Al/Al₂O₃/SiC/Mg-SS316L composite bimetallic sheet

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Abstract

Corrosion impact and characteristics on Al/Al₂O₃/SiC/Mg-SS316L composite bimetallic sheet have been studied for CuSO₄ and H₂SO₄ (CuST) based solution under room temperature. The observations from the microstructure, EDX and XRD analysis for the clad and its interfaces depicted the presence of various primary α -Al and Cr based intermetallics with parent clad materials in Al₂O₃ and SiC combinations. A comparative evaluation for primary Al₂O₃ and SiC clad materials shows a specific difference between the phase formation and intermetallics on the corrosion surfaces. Thinner and bi-metallic corrosion resistance for the SiC/Mg-SS316L clad is dominating as compare to the Al₂O₃/Mg-SS316L clad with intermetallics compounds of nano aluminum powder.

Keywords: Conventional cladding, Al-nano powder, SS316L, Corrosion, Al₂O₃, SiC, CuST

1. Introduction

The Cr coating developed has many advantages such as excellent resistance to water corrosion, high-temperature steam oxidation resistance, fine irradiation resistance, good adhesion with SS316L substrate, and favorable thermal compatibility to Al/Al₂O₃/SiC/Mg alloys [1-4]. Conventional cladding is extensively utilized in industries such as chemical processing, mining, power generation, and marine applications [1, 5-9]. But synthesized products need various protections against the corrosion and wear due to various applications like building structures, insulation, surface integrity etc. It offers significant cost savings, potentially reducing expenses by up to 80% compared to solid alloys [9-12].

Metallic engineering structures and applications are generally extensive used of high-strength SS316L, which is based on the Al, Mg, Al₂O₃, SiC, Ti and many more alloying elements and ceramics [13, 14]. However, it is less availability for modifications to corrosion fatigue, stress corrosion cracking, and pitting corrosion for these applications. These issues may cause significant doubts about the utilization of these alloys and elements [11, 15]. The use of corrosion protection methods, such as inhibitors, anodizing, conversion coatings, primers, and paint finishes, is currently the primary method of preventing corrosion of high-strength SS316L [3, 11]. For this, conventional surface cladding is thought to provide an additional option that could solution regarding the shortcomings in relation to the poor corrosion characteristics [5-8, 12].

Therefore, further research is needed to fill these gaps and provide a comprehensive understanding of the combined effect of perforation and nano-Al₂O₃-SiC Coarse Al-Mg on corrosion resistance across different materials and applications. However in this experimental work, corrosion characteristics for the Al-Al₂O₃/SiC-Mg based clad for the SS316L substrate

synthesized by conventional process has been investigated for CuSO_4 and H_2SO_4 mixed solution in general atmospheric conditions. After corrosion test, generation of different phases and intermetallics are identified and reported according to microstructure, EDX and XRD evaluation.

2. Materials and Methods

2.1 Preparation of Clad Material

In the experimental work combination of nano size powder particles was used for the ball milling process. Initially Al_2O_3 (Alpha nano form, M.W. 101.96), SiC (Nano form, M.W. 40.10), Mg (Mesh Size 36, A.W. 24.31), Al powder (Mesh Size 325, A.W. 26.98) particles were preheated to remove moisture. Then a combination of these powder particles were placed inside the ball milling setup for refining and mixing. After ball milling, mixed powders were blended inside a glass container and for proper mixing a gelatin gel has been used. During the process gelatin gel was prepared by the help of gelatin powder and lukewarm water of 70°C . A continuous stirring process was used to prepare gelatin gel for a drop of temperature from 70 to 50°C . As the powder of gelatin spent time inside the warm water, have tendency to expand and ability to generate thick slurry. Up to the reaches room temperature gelatin slurry converted to the gel and becomes thicker.

2.2 Substrate preparation

Stainless steel plate of 316L (chemical composition as represented in table 1) is cleaned by industrial grade solvent (acetone) and cut in the size of $30 \times 30 \text{ mm}^2$ contact area as a substrate. Cutting of the substrate was conducted by laser fiber cutting technique at 1000watt (Satguru enterprises Pvt. Ltd. Kanpur). To avoid any type of heat affected effect and oxidation on the SS316L plate a continuous chemical solvent (Nitrogen spray atmosphere) was provided. A

matrix of 4x4 perforation of size 0.8mm in diameter was provided on the substrate. Drawing of perforation is represented in our previous publications [13, 14]. During the perforation a continuous monitoring of the surface was taken care to maintain the orientation of the holes for uniformity. This perforation has ability to provide increase in the heat transfer rate and diffusion between the clad and substrate.

2.3 Compaction and Sintering

Prepared clad powder mixed with gelatin was placed in between the two perforated substrate of SS316L. For 1.5mm thick plate (one side of the bi-metallic substrate), approximately 0.3mm thick clad interface is provided in between the substrate plates before the compaction. Initially substrate plates were pressurized by conventional masses (approx. 5kg) at room temperature to just settlement and initial compatibility at room temperature for a 2 hrs. Next, plates were placed in between compaction contact (spring compaction machine) under an effective pressure of 22.2 MPa. This mild pressure continuously provided for 30 mins. And during this step effective thickness of clad is observed as 0.25mm due to removal of excess amount of gelatin gel. It has been observed that some amount of fine aluminum particles were squeezed out with gelatin gel on the lateral surface of the substrate. This might be the effect of compatible mixing of aluminum powder with gelatin rather than other added particles (Al_2O_3 , SiC and Mg). After compaction green compact clad-substrate plates were placed inside the hot air oven for 06 hrs under 50°C environment to remove any type of moisture on the surfaces.

Green compact of clad substrate were placed inside the industrial muffle furnace for conventional heating. For diffusion of the particles several temperature range were investigated and it was found that up to 1100 °C no any major effect was observed. For heating arrangement

substrate plates were placed over ceramic grooved plates. On a temperature of 1300 °C outer layer of lateral direction was seems to be hot red melted then rise in temperature was stopped and for equilibrium of 1400 °C plates were continuously heated for 30 mins. Muffle heating was stopped and cooling was provided itself inside the muffle furnace. During conventional sintering process argon gas was provided as an inert gas environment. Steps used in the process summarized in figure 1.

2.4 Corrosion Test

Corrosion test were conducted for the 8 gm CuSO_4 + 2ml H_2SO_4 +500 ml Distilled water (CuST) for 5 mins contact duration as per ASTM-A-380 standard. Before the electrolyte mixing, samples were properly cleaned to remove moisture and any possible dust. Electrolyte droplets were softly dropped on the clad surfaces during the test under a room temperature of 35-37°C.

2.5 Characterization and Evaluation

For the evaluation of processing impact with a consolidated influence of ceramic based clad was conducted by microstructure, EDX and XRD. Optical microscopy was also provided to identify the effect of sintering on perforated zone and interface. Microstructure evaluation has been conducted by the help of FESEM equipped with EDX facility (Make: ZEISS SUPRA 40 VP instrument). For the interfacial identification of different elements XRD (Make:) was conducted. X-ray diffraction (XRD) evaluation was carried out in the range of 20°-90° with a step size of 0.02° using a PANalytical expert instrument.

3. Results and Discussion

The cross-sectional SEM picture and related crystal-logic data of as-deposited nano- $\text{Al}_2\text{O}_3/\text{SiC}$ -4%Mg-clad with a thickness of roughly 93µm are displayed in Fig.2 and 3. As seen in

Fig. 2, there were no visible micro-cracks or pores at the Al_2O_3 Clad/SS316L Substrate, suggesting that the Al_2O_3 Clad was firmly adhered to the SS316L substrate [13, 14]. As illustrated in Fig. 3, the Al_2O_3 clad had columnar grain morphology with a width of 0.2–2 μm . According to the various locations for the surface of clad, in Figure 3 and 4, the SS316L substrate had equiaxed grain morphology with sizes less than 20 μm .

Regarding oxidation, the oxide scale and elemental diffusion behaviors for corrosion show significant changes as the temperature rises. Therefore, figure 4 and 5, displays the EDX observations to elemental identification for 2% Al_2O_3 -4%Mg-SS316L and 2%SiC-4%Mg-SS316L respectively [13, 14]. Figure 4 displays the EDX map scans and cross-sectional morphologies of Al_2O_3 -coated SS316L alloy claddings following corrosion. Similar processing parametric zone for SiC-coated SS316L is observed in figure 5. Respective elemental oxidation weightage is summarized in table 2 for EDX spectrum represented in figure 4 and 5.

The Cr-rich SS316L substrate, residual Al_2O_3 Clad, and SiC layer produced a three-layer structure from the outside [16-18]. Accordingly, figure 6, the clad structure that was seen on the clad side as the room temperature and corroded after 5 mins. Above the substrate, the Al_2O_3 -Cr diffusion layer developed. A straight Al_2O_3 /Mg/Cr contact was indicated by the homogenous and flat Al_2O_3 -Mg-Cr layer seen at the interface zone in the cross-sectional SEM images of Figure 6. Moreover, Al_2O_3 -rich precipitates were seen on the SS316L-Cr rich substrate (marked by red boxes), as seen in Fig. 6, but this observations were absent for SiC in the figure 7. The intermetallic α -Al-SiC-Mg intermetallics phase forms for 2%SiC-4%Mg-SS316L Clad, based on the Al-Mg phase diagram. The absence of precipitates on the SiC substrate at could be because the diffusion rate of Al_2O_3 atoms is lower as comparison to the other substances [12]. The Al_2O_3 -Mg/SS316L clad contact changed from being flat to wavy in figure 8. In certain areas, as the

Al₂O₃-based clad became thinner as comparison to SiC-based clad interface. The undulation of the Al₂O₃/Mg corrosion interface correlated with the thickening-thinning transition of the Al₂O₃-Cr layer [19]. The reaction between the outward distributed Cr and Al₂O₃-Cr was facilitated by the convex points of the Al₂O₃/Al-Mg-Cr interface, which were always connected to the grain boundaries of the remaining Al₂O₃ Clad. Similar impact is observed in figure 8 for SiC-based clad interfaces [3]. Some Cr-diffusion channels almost reached the Nano-Al/Al₂O₃ interface, as seen in the Cr mapping of Fig. 9 and XRD evaluation as shown in figure 10, suggesting that a redox reaction between Al₂O₃-Mg and Cr occurred.

Because the redox reaction happened more forcefully, the oxide scales were almost broken and the Al₂O₃ Clad thickened considerably [20]. The Al₂O₃-SiC/Al-Cr contact, which had been undulating, became rather straight. Compared to SiC-Mg-SS316L, where the CrO₂ layer formed on the substrate, Figure 10 represented various XRD elemental distributions over the clad-surfaces after the corrosion test [21]. The Al₂O₃ Clad failed in earlier stage which might be identified by the various intermetallics and phases as shown in figure 10. It is clear the fewer amounts of peaks are observed in figure 10 for XRD results as comparison to the other independent elements. The CrO₂ layer did not form on the Cr-particles on the substrate, suggesting that the Al₂O₃ Clad can stop oxygen from penetrating the substrate [9]. From XRD elemental observation, independent foreign elements such as S and Cu, which were not a dominating part of clad as well as substrate, identified with similar in EDX mapping as shown in figure 4 and d 5 and table 2. EDX and XRD results are suggesting limiting involvement of S and C and some higher amount of Cu. But all these elements are dominating by the independent Cr, Al, Mg and O. Typical examples of reaction clads generated on the SS316L substrate are depicted in Figure 11. While epitaxial crystal formation was consistently seen at the fusion zone-

substrate interface (Fig. 8), the majority of the time, a strong binding between the top reaction layer and the fusion zone (Solidified Al-precipitate) was seen (Fig. 11). The comparatively coarse constituent particles that were present in the wrought structure were removed due to the process quick cooling, which is not present in the fusion zone [20]. Figure 10, the XRD data of the clad surface of the Al–SiC–Mg–xCr (x=independent value) system, which contained several chromium/magnesium aluminide phases (marked by red box), are observed in figure 11. The existence of Al, Mg, Si, Cr, and Al₂O₃ in the reaction Clad is confirmed by the EDX examination results (Fig. 4). Table 3 provides a summary of the XRD findings for the three systems. There were α -Al₂O₃ and Cu–Al₂O phases in every combination. CrO₂ and Mg based phases are most common for the both the combinations with some independent phases are observed for Cu, C and Si.

The findings indicate that, with the exception of the Al–CuO–SiC system, the clad specimen's corrosion impact density was an order of magnitude lower [13, 17]. All clad specimens, however, did not appear to have a passive zone. It is thought that the reduced metals and different intermetallic phases are present in the reaction Clads, which are not uniform. This may cause surface-bimetallic corrosion and compromise the integrity of the Clads [18, 22]. In the event that the break penetrates the entire Clad, corrosion attack at the Clad-fusion zone interface may happen easily [22]. Bimetallic corrosion attack can, in fact, happen easily in the reaction clad. For instance, when looking at the Al–Mg–SiC–Cr system, the reduced Cr metal, the intermetallic complexes Al₂CrMg and Al₄Cr₉, are cathodic with regard to aluminum. Generous corrosion pits will result from the progressive dissolution of the anodic aluminum. The corroded specimen in Figure 11 shows that it was severely attacked by pitting corrosion, which may help to explain why the Al–Mg–SiC–Cr combination has such a low corrosion resistance. For the Al–

Mg-Cr and SiC-Mg-Cr combinations (Fig. 9) and XRD results, the situation was far better, with only isolated corrosion pits visible. At this point, it is unclear why the Al-Mg-Cr and SiC-Mg-Cr combinations outperformed the Cu, C and S based elements. Nonetheless, it was thought that the slight potential difference between decreased Si and Al would serve to decrease the intensity of bimetallic assault in the Al-Mg-SiC-Cr combination.

4. Conclusions

- $\text{Al}_2\text{O}_3/\text{SiC}/\text{Mg}$ clad for SS316L substrate contains Al and Cr based might be generated by CuSO_4 and H_2SO_4 in between the added nano powders in the clad.
- Al/ Al_2O_3 /SiC/Mg-SS316L based specimens, exhibited differential corrosion resistance for different intermetallics and precipitate of Cr which has potential to increase in corrosion resistance.
- According to microstructure, EDX and XRD, a specific difference for the processing parameters and primary Al_2O_3 and SiC is obtained for the phases generated for the surface corrosion.

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Data Availability Statement

This manuscript is free from any data use in other sources.

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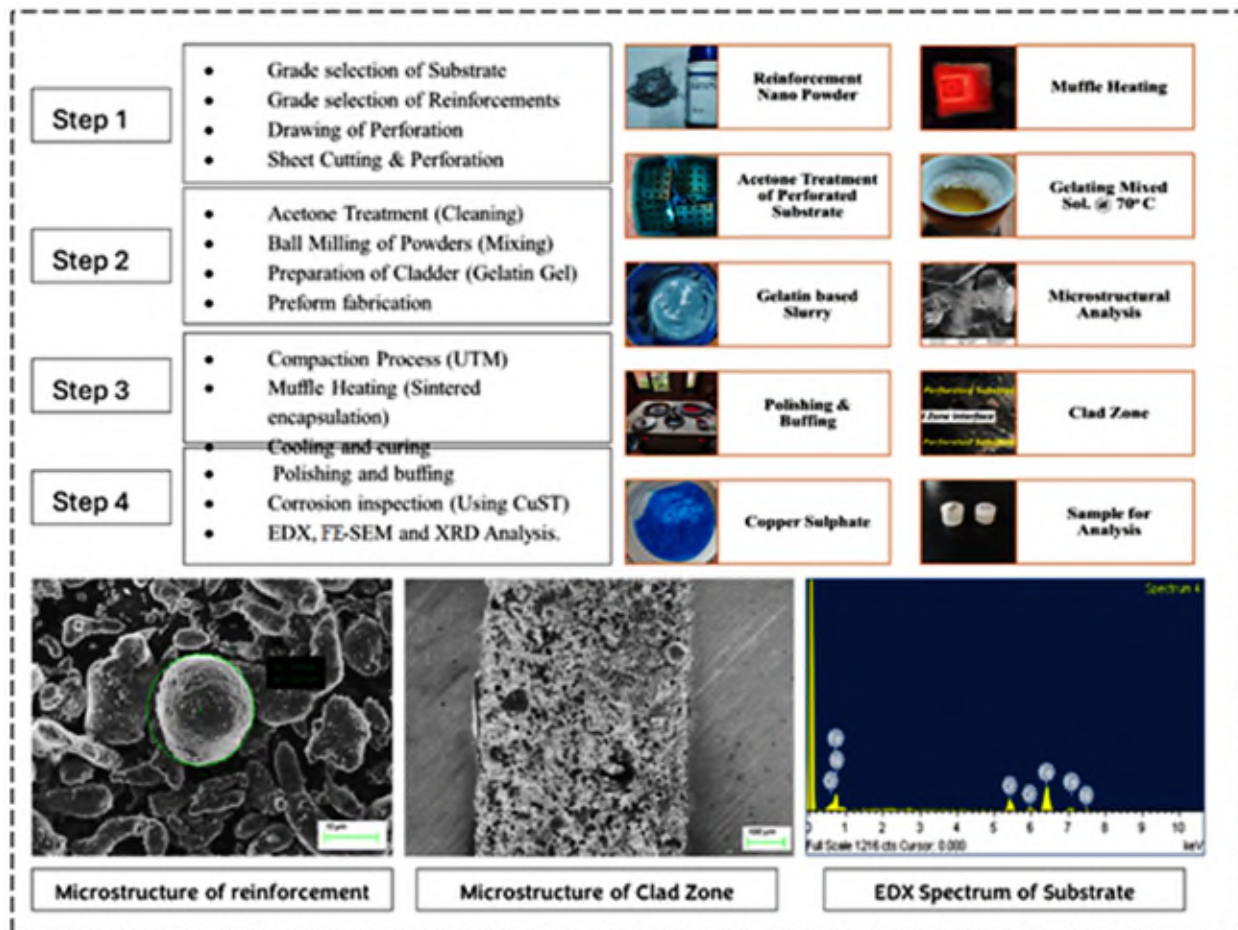


Figure 1: Processing scheme for the 2%Al₂O₃/SiC-4%Mg-SS316L clad sheet

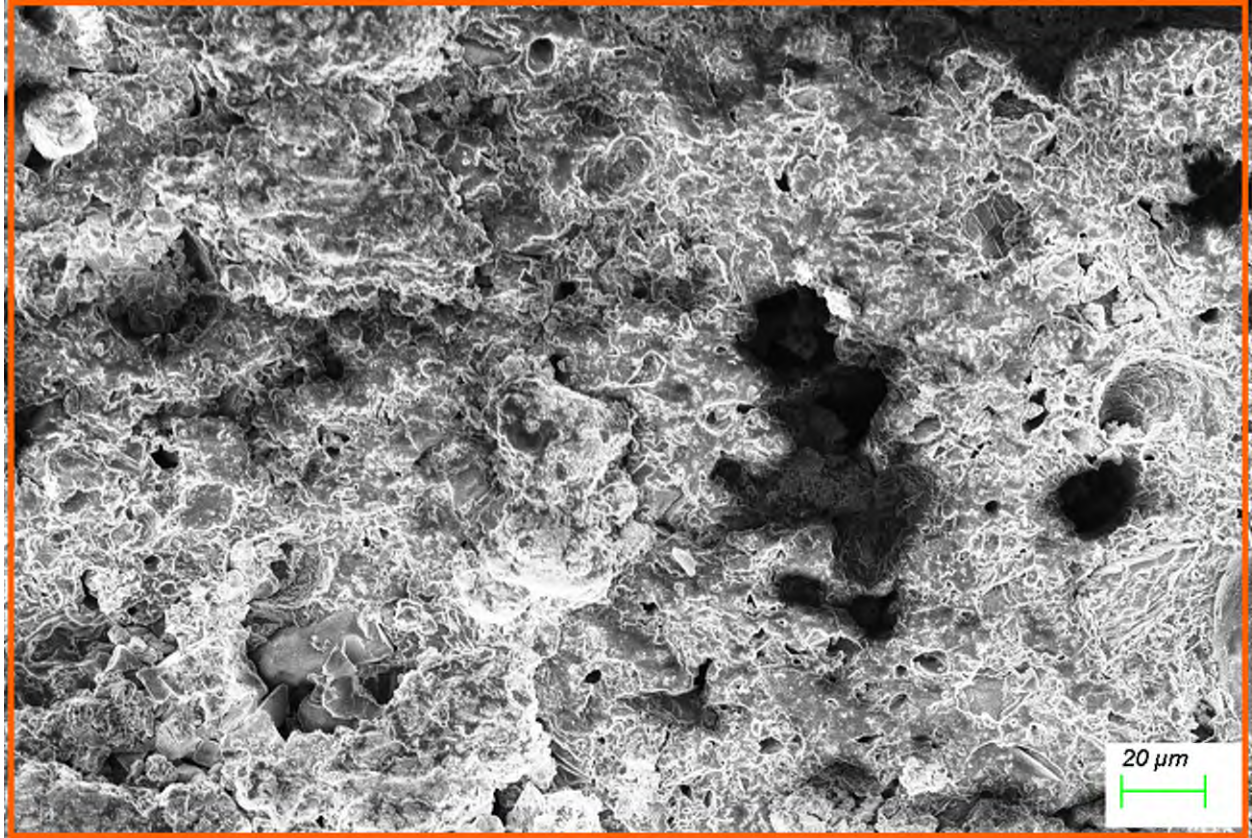


Figure 2: Microstructure images for clad 2%Al₂O₃-4%Mg-SS316L

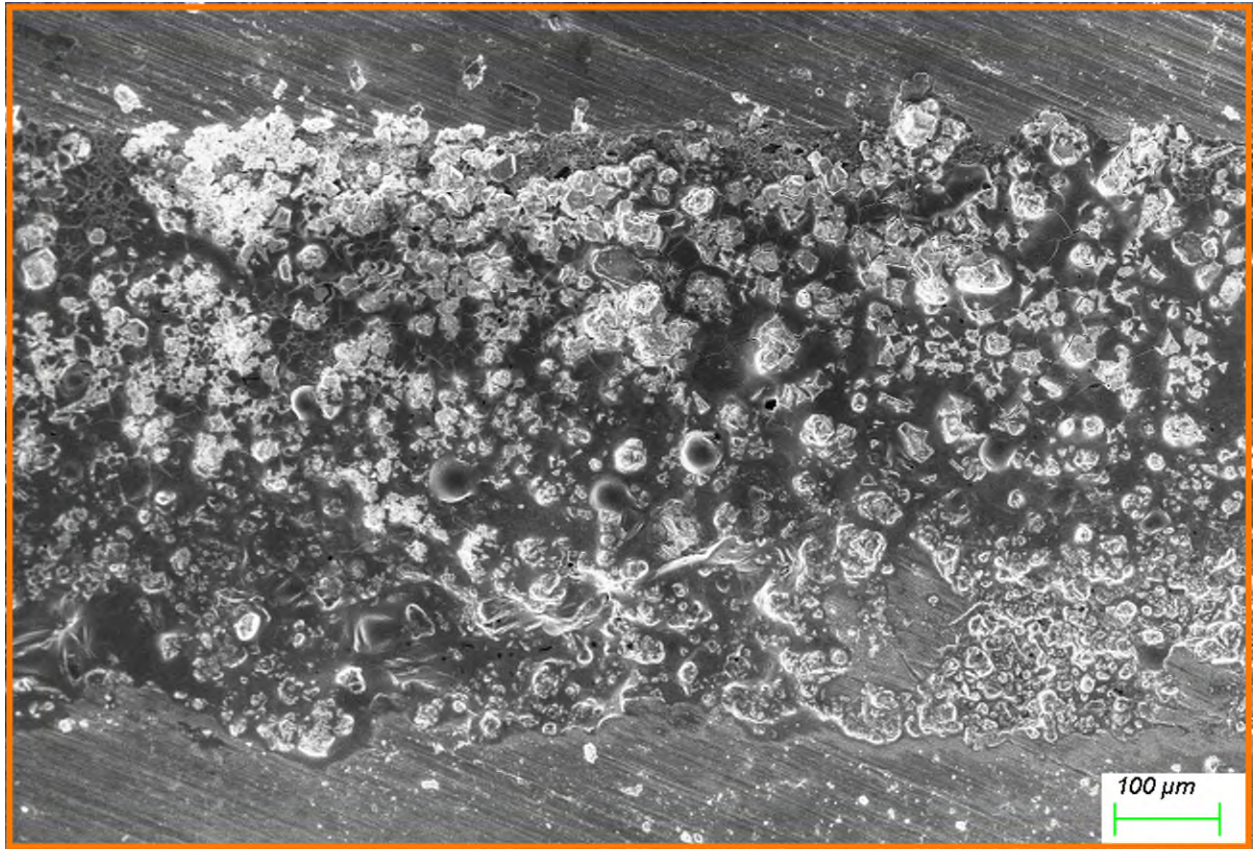


Figure 3: Microstructure images for clad 2%SiC-4%Mg-SS316L

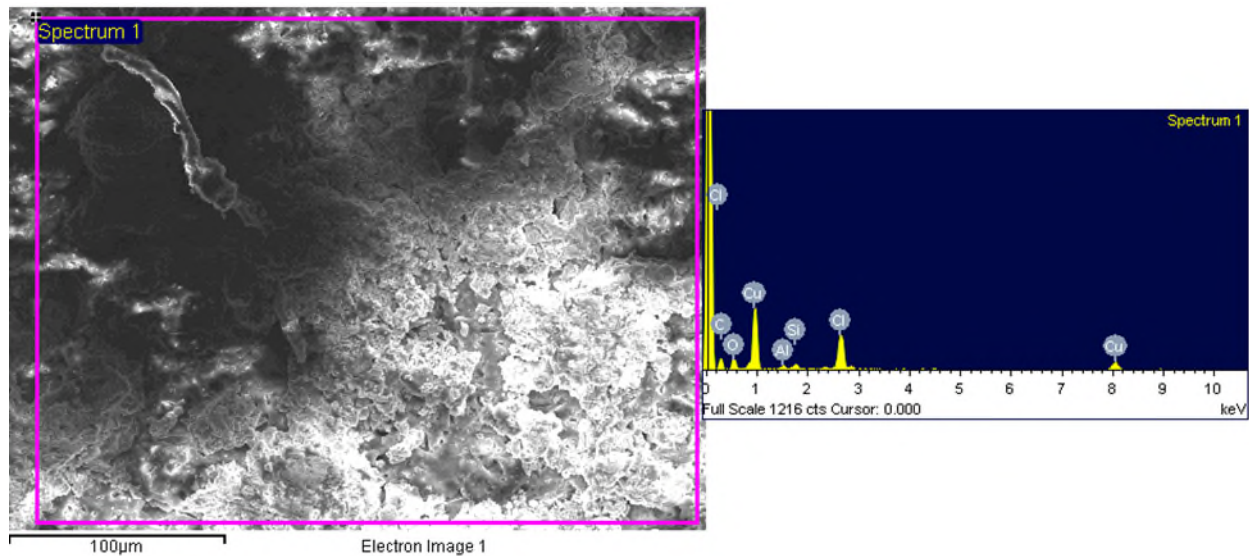


Figure 4: EDX mapping area for 2%Al₂O₃-4%Mg-SS316L with corresponding EDX-spectrum

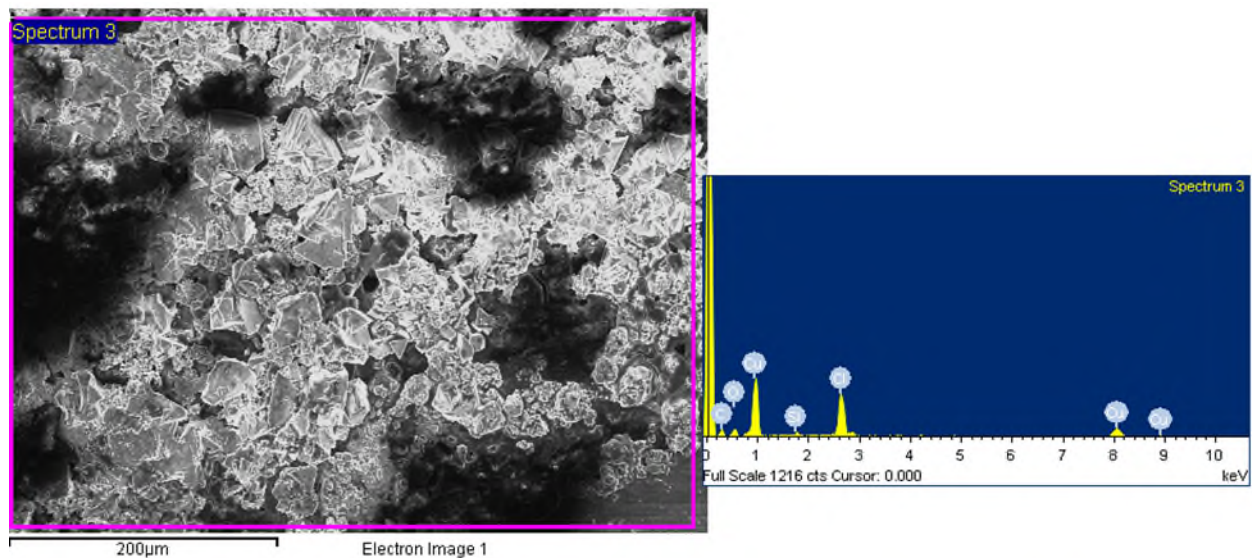


Figure 5: EDX mapping area for 2%SiC-4%Mg-SS316L with corresponding EDX-spectrum

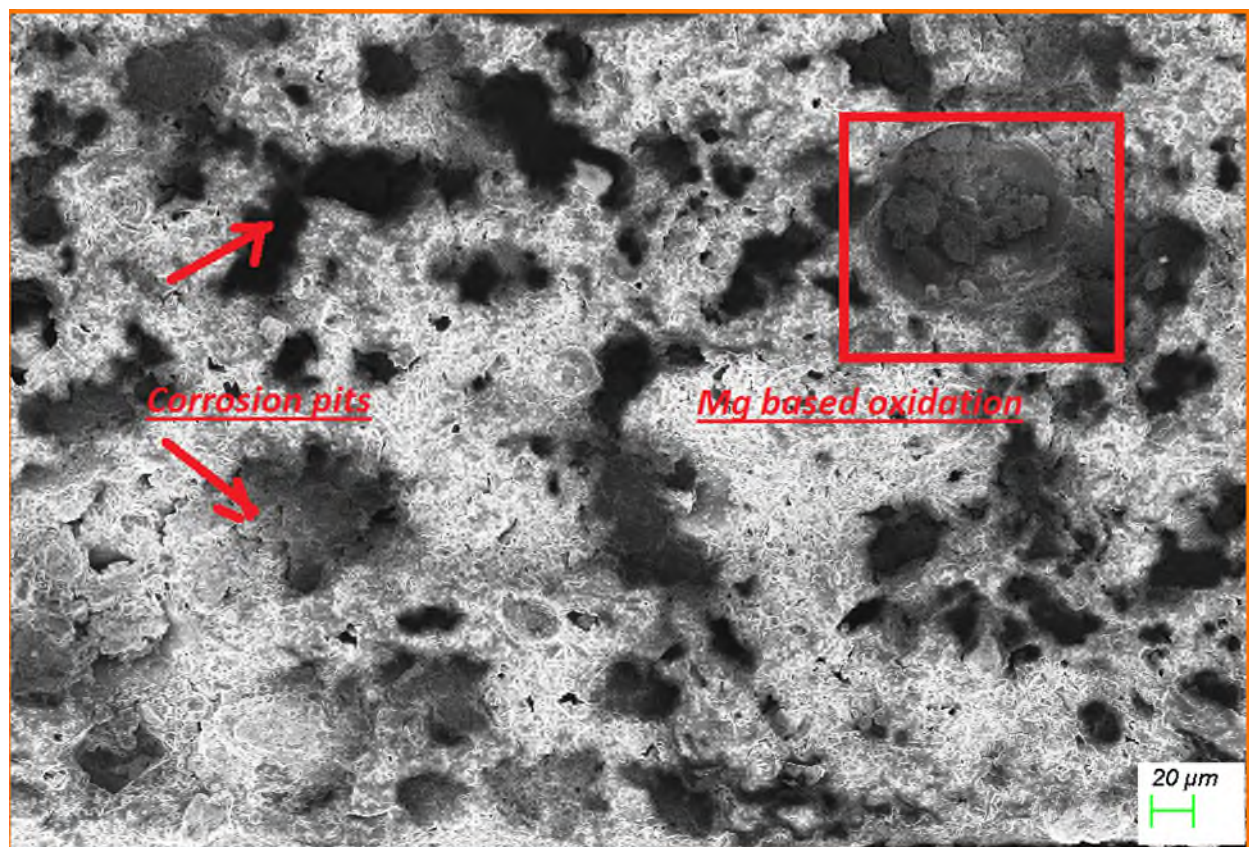


Figure 6: Microstructure for corroded 2%Al₂O₃-4%Mg-SS316L

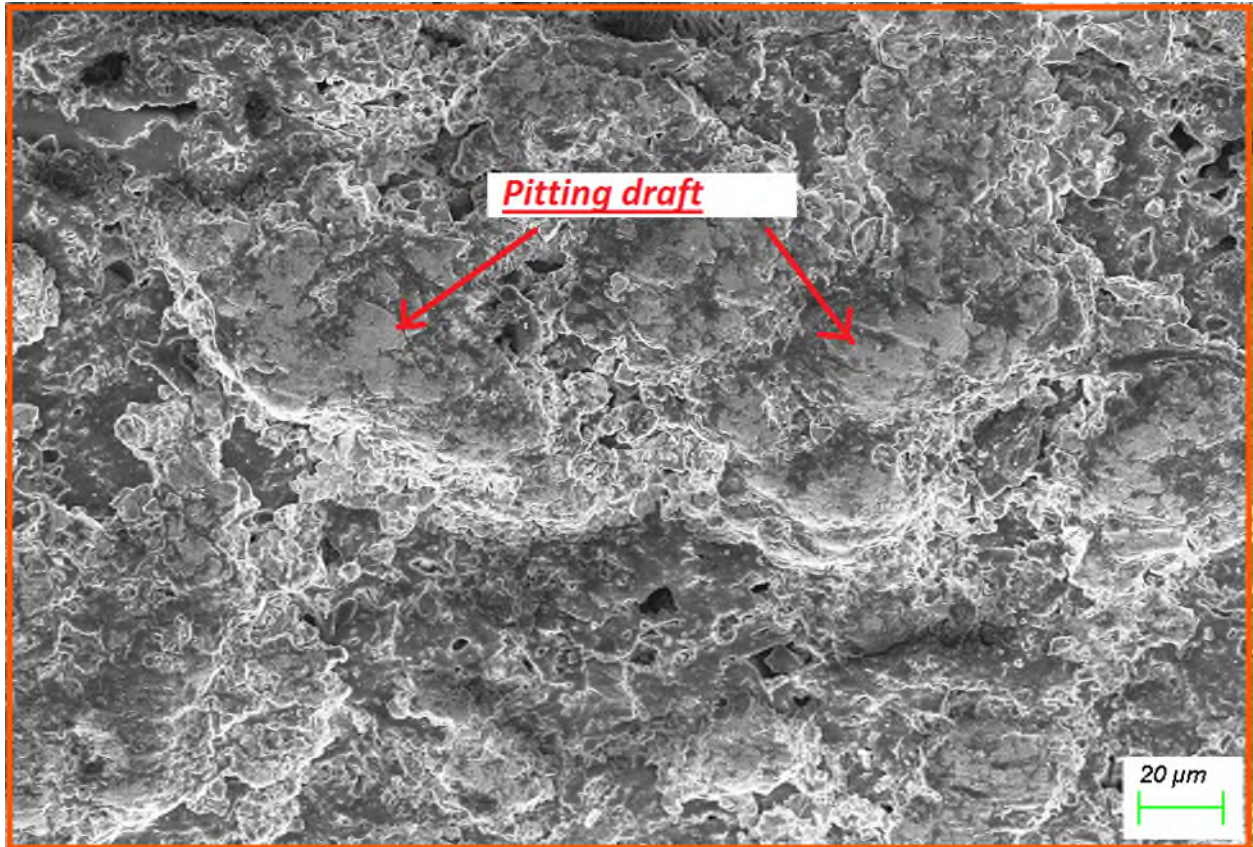


Figure 7: Microstructure for corroded 2%SiC-4%Mg-SS316L

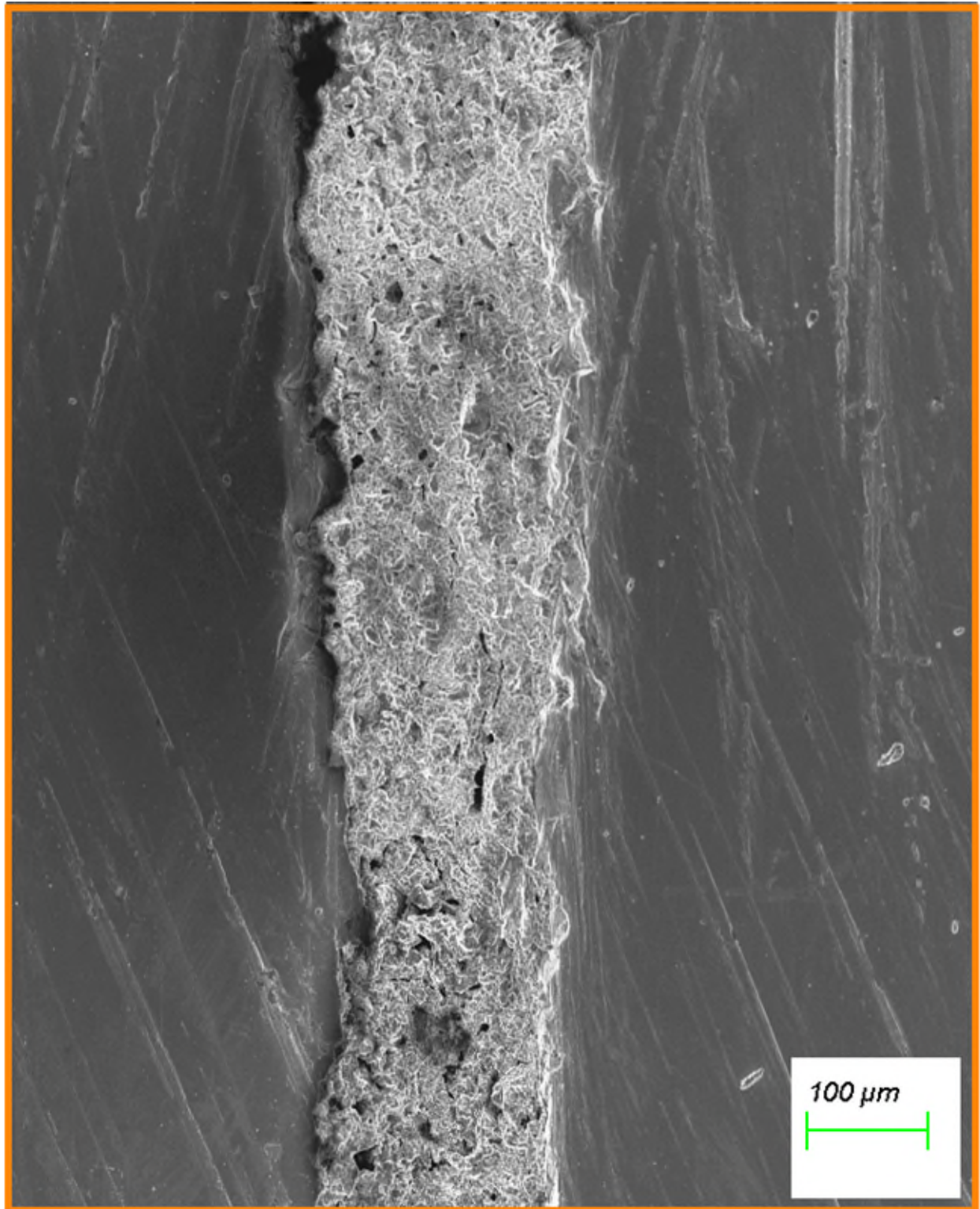


Figure 8: Microstructure for Clad-Substrate interfaces for 2%Al₂O₃-4%Mg-SS316L

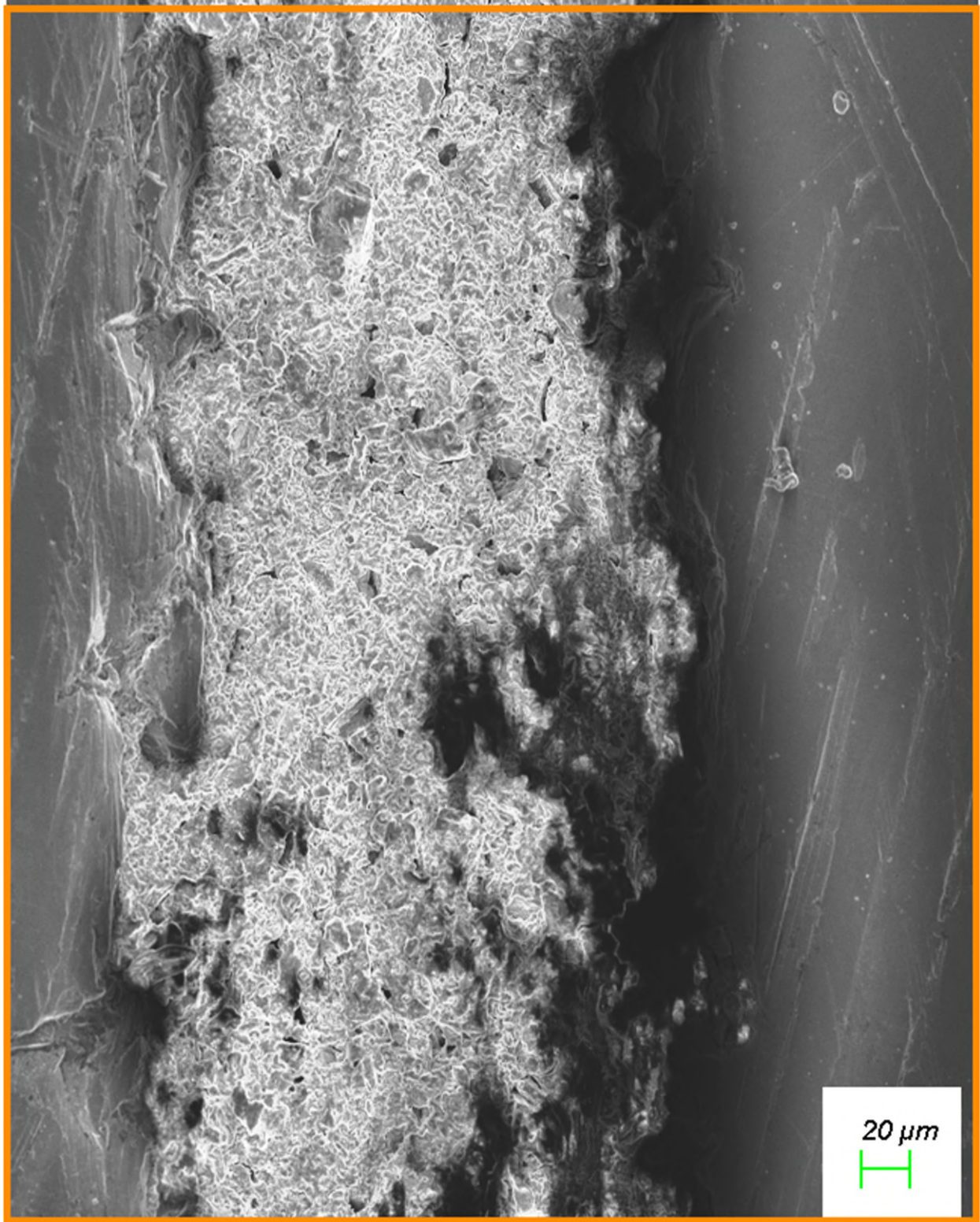


Figure 9: Microstructure for Clad-Substrate interfaces for 2%SiC-4%Mg-SS316L

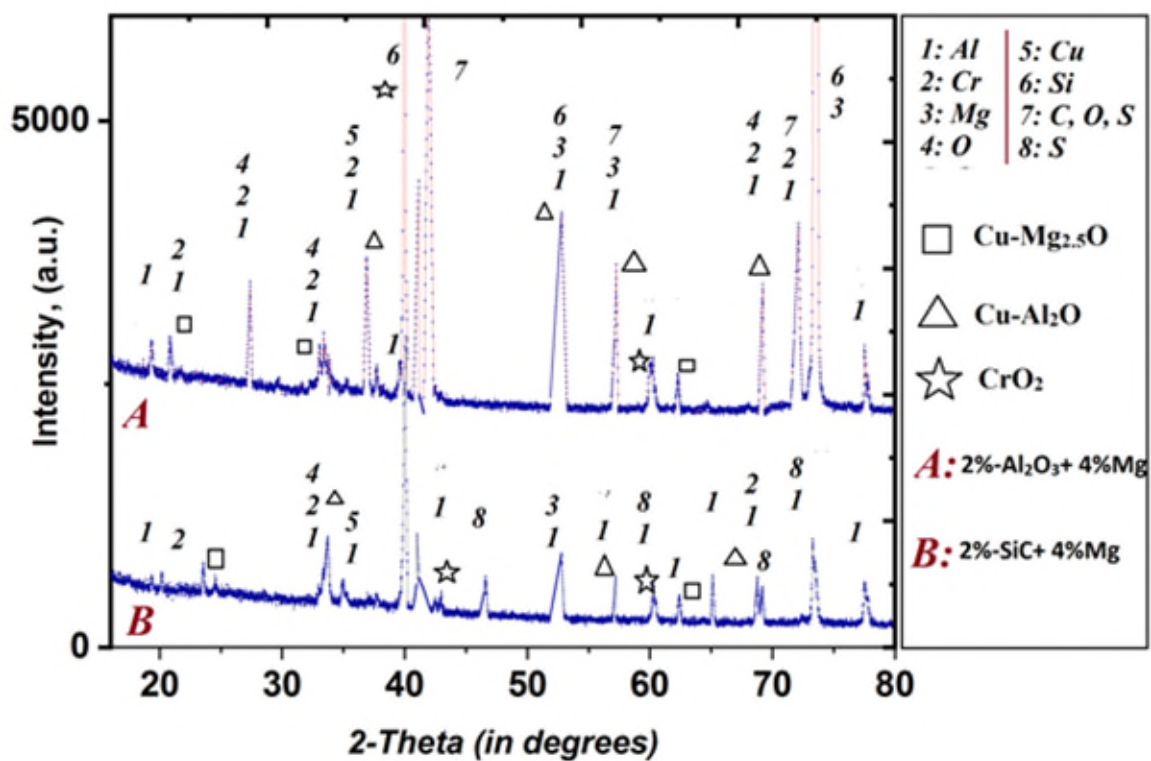


Figure 10: XRD evaluation for the 2%Al₂O₃/SiC-4%Mg-SS316L

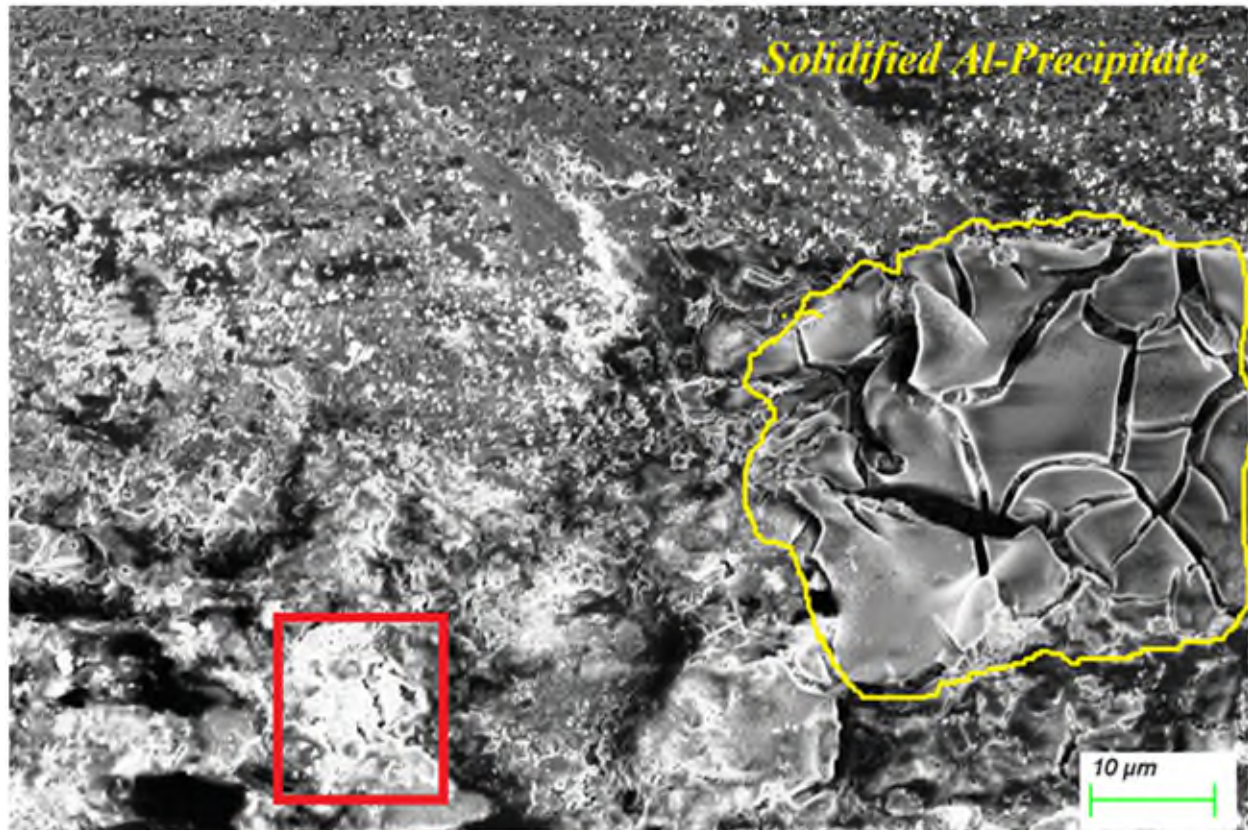


Figure 11: Microstructure image for Al_2O_3 precipitate on the clad interfaces after corrosion test

Supplementary Files

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