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ASSESSMENT OF ALUMINIDE COATING INTEGRITY BY USING ACOUSTIC EMISSION

Mateusz KOPEC*, Dominik KUKLA, Zbigniew L. KOWALEWSKI

Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland
*corresponding author, *mkopec@ippt.pan.pl*

Coatings are essential for protecting high-temperature components in aerospace and power generation industries. This study evaluates the integrity of aluminide coatings on MAR-M247, a nickel-based superalloy, under uniaxial tensile loading using acoustic emission (AE). Aluminide coatings, deposited via chemical vapor deposition (CVD), provide oxidation and corrosion resistance but are prone to damage under operational stresses. AE monitoring, a nondestructive evaluation method, detects transient elastic waves associated with damage events such as crack initiation and delamination. By analyzing AE signal characteristics like amplitude and energy, this research identifies acoustic signatures indicative of coating degradation. The findings highlight AE's potential for real-time damage assessment, enabling early detection and predictive maintenance strategies in high-temperature applications.

Keywords: coatings; acoustic emission; nickel alloys; nondestructive testing.

1. Introduction

Thermal barrier coatings (TBCs) are indispensable in high-temperature applications, particularly in industries such as aerospace and power generation, where components are subjected to extreme thermal and mechanical loads (Barwinska, 2023). These coatings serve as protective layers that insulate and shield the underlying metallic substrates from excessive heat, oxidation, and corrosion. By doing so, they enhance the durability, performance, and operational efficiency of critical components such as turbine blades and combustion chamber liners. Among the various substrate materials used in such applications, MAR-M247 – a nickel-based superalloy – is a prominent choice due to its superior mechanical strength, creep resistance, and thermal stability at elevated temperatures (Kopec, 2024b).

Aluminide coatings are applied to MAR-M247 to provide additional protection against oxidation and high-temperature corrosion (Kopec, 2024a). These coatings, often produced via processes such as chemical vapor deposition (CVD) or pack cementation, form a stable alumina or chromium oxide layer upon exposure to high temperatures, which acts as a barrier to oxygen diffusion. Despite their excellent protective properties, aluminide-based coatings are susceptible to damage due to thermal cycling, mechanical loading, and prolonged exposure to extreme environments (Kukla, 2020). Such damage manifests itself in various forms, including

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cracking, delamination, and spallation, which compromise the coating's integrity and lead to potential component failure. The ability to monitor and assess the integrity of coating systems in real time is crucial for preventing unexpected failures and optimizing maintenance schedules (Kukla, 2021a). Conventional inspection techniques, such as eddy current, visual examination, microscopy, and ultrasonic testing, are often time-consuming, invasive, or limited in their ability to detect early-stage damage (Kukla, 2021b). In contrast, acoustic emission (AE) monitoring has emerged as a powerful nondestructive evaluation (NDE) method for detecting and characterizing damage processes in real-time. AE monitoring involves the detection and analysis of transient elastic waves generated by the rapid release of localized energy within a material, typically associated with events such as crack initiation, crack propagation, or interfacial delamination (Andrews & Taylor, 2000). This study investigates the application of AE monitoring to evaluate the integrity of aluminide coatings deposited on MAR-M247 when subjected to uniaxial tensile loading. Uniaxial tension serves as a simplified mechanical loading condition to simulate the stresses that coating systems may encounter during service, particularly those associated with mechanical deformation, thermal gradients, and operational vibrations. By correlating AE signal features – such as amplitude, frequency, and energy – with the progression of damage, this work aims to identify characteristic acoustic signatures that can serve as indicators of the coating degradation. The integration of AE monitoring with traditional post-mortem analysis methods, such as scanning electron microscopy (SEM) and metallographic evaluation, provides a comprehensive approach to understanding the failure mechanisms in coating systems. The findings of this study hold significant implications for industries reliant on high-temperature components, where the early detection of coating failure is essential to ensure reliability, safety, and cost-effectiveness. By advancing the understanding of AE monitoring in the context of aluminide-coated MAR-M247, this research contributes to the broader effort of implementing advanced NDE methods for predictive maintenance and life-cycle management of critical engineering systems.

2. Materials and methods

MAR-M247 nickel superalloy specimens were produced using a conventional casting technique (Fig. 1a). Aluminide coatings were applied through the chemical vapor deposition (CVD) process. The deposition was carried out at a temperature of 1040 °C and an internal pressure of 150 mbar, utilizing optimized CVD parameters in a hydrogen-protective atmosphere, with deposition durations of 8 and 12 hours (Kopec, 2024b). A representative cross-section of a MAR-M247 specimen with a 40 μm coating is shown in Fig. 1a. The microstructure exhibits a two-layer configuration: a homogeneous zone of a secondary solid solution β (NiAl) phase and a heterogeneous NiAl matrix (dark gray) containing dispersions of a Ni_3Al phase (light gray). Acoustic emission assessment was conducted to evaluate its applicability to identifying the cracking of the coating layer based on the acoustic effect associated with the crack propagation. The tests were performed on a specimen subjected to static tension, using four measurement sensors mounted at the lower and upper parts of the specimen, on both sides (Fig. 1b). This sensor arrangement made it possible to separate the acoustic emission signals from the gripping sections of the specimen from those from the measurement area, where crack propagation in the coating was expected. The measurements were carried out using the AMSY-5 M6-2 Acoustic Emission System from Vallen and VS-150 type sensors with a preamplifier (Fig. 1b). The tests were based on the assumption that cracks initiated in the brittle aluminide layer would generate an acoustic emission signal in the form of an elastic wave propagating through the specimen material. The AE sensors detect and convert the waves into electrical signals, while the measurement channel of the AE system parameterizes the signal and records its progression. The tests were performed during tensile tests with a traverse speed of 0.05 mm/sec.

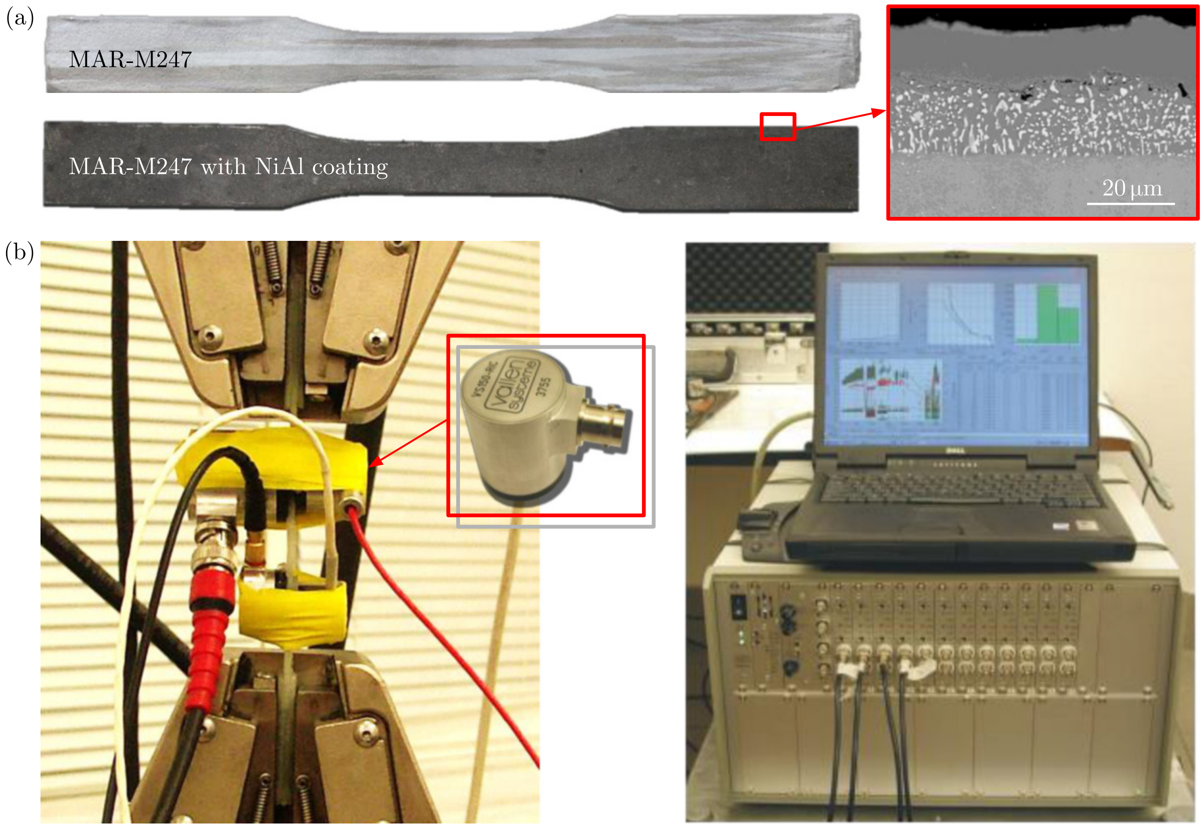

Fig. 1. (a) General view of casted MAR-M247 specimen and the same specimen with aluminide coating with additional magnification of coating cross-section; (b) specimen fixed in the grips of the testing machine with VS-150 type AE sensors and a preamplifier.

3. Results and discussion

The results indicate a significant increase in the number of acoustic hits as well as their energy and amplitude in the tensile specimen with the coating (Figs. 2a and 2b). It can be inferred from other research conducted on materials and structures under load that signals with the highest energy may be associated with coating failure in the specimen. Since the specimens only differed in the presence of the coating (with the same core structure), the noticeable changes in the obtained results are solely related to surface effects.

In addition to crack formation, acoustic effects related to the loss of coherence between the coating and the substrate may also occur, which is a result of differences in the susceptibility of the two materials to plastic deformation (Fig. 2c). It could be further confirmed by the distribution of the parameter D, which represents a duration of a specific event in microseconds and was categorized by different ranges: $0 \leq D < 500\,\mu s$ (green points); $500 \leq D < 1000\,\mu s$ (red points); $1000 \leq D < 10000\,\mu s$ (yellow points). Shorter times ($0\,\mu s$–$500\,\mu s$) correspond to weaker or less severe events, while longer times ($1000\,\mu s$–$10000\,\mu s$) indicate stronger emissions related to significant material changes. One could observe that AE is a highly effective NDT technique for monitoring and detecting cracks during tensile testing, particularly for complex materials like MAR-M247 with an aluminide coating. The combined structural integrity of both the substrate and the coating is vital during tensile testing, as failure can occur in either phase or at the interface between them. AE can provide a detailed and real-time assessment of the material's behavior under stress, which is crucial for understanding how cracks initiate, propagate, and affect the overall performance of the material. During tensile testing, the deformation of the material generates microstructural events such as the formation of dislocations, crack initiation,

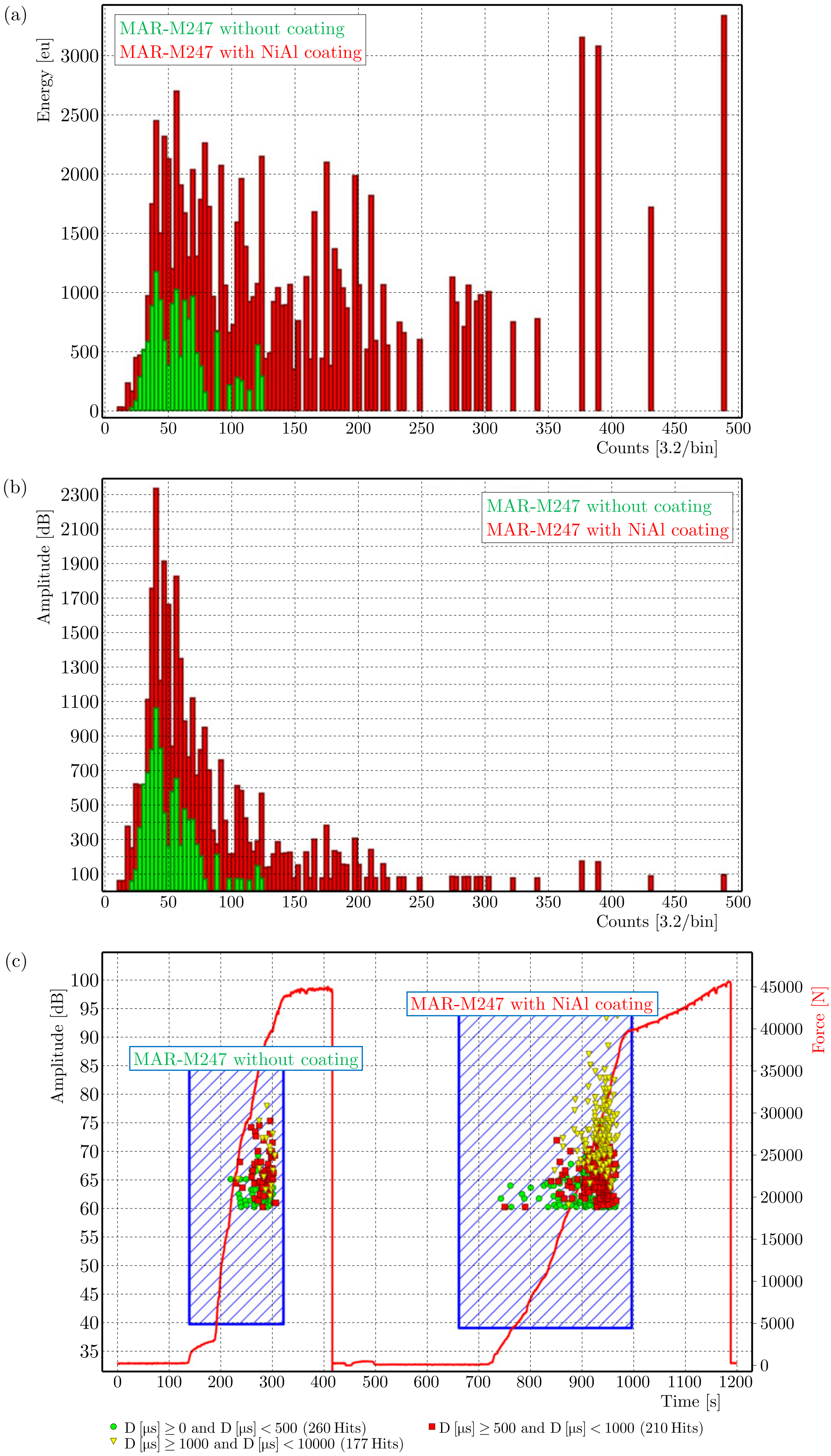

Fig. 2. Dependence of signal energy (a) and amplitude (b) of acoustic emission on their count, recorded during the tensile testing of specimens with and without the coating. Amplitudes of acoustic emission signals recorded during the tensile testing of specimens with and without the coating, along with the tensile curve (c).

and the growth of these cracks into larger fractures. AE detects the high-frequency sound waves or "pings" that are emitted when these energy-releasing events occur. When a crack forms, it generates a burst of elastic waves that travel through the material. AE sensors positioned on the surface of the material can detect these waves, thus enabling early identification of the damage, before it becomes visually detectable. The ability of AE to pick up these emissions provides critical insight into the initiation of cracks at stress concentration points, such as grain boundaries, inclusions, or other microstructural imperfections, which are common in materials like MAR-M247. This early detection is invaluable because it enables timely intervention, potentially preventing catastrophic failures. AE is also particularly useful in monitoring crack propagation during tensile testing. As cracks grow, they emit higher intensity AE signals, and the frequency and amplitude of these signals can be correlated with the size and rate of crack propagation. In the case of MAR-M247, the evolution of cracks can occur in both the aluminide coating and the base alloy, and AE can help differentiate the sources of emissions. For instance, cracks in the aluminide coating might produce different acoustic signatures compared to cracks in the nickel-based alloy due to the differences in their mechanical properties, such as stiffness and hardness. AE can also detect any delamination or debonding at the interface between the aluminide coating and the MAR-M247 substrate, which is crucial for understanding the behavior of coated materials under stress. This ability to monitor both phases of the material in real-time provides a more comprehensive understanding of the material's failure modes, particularly in materials that are prone to complex failure mechanisms, like those with coatings. Furthermore, AE can assist in the assessment of localized damage in regions where the aluminide coating might be subject to plastic deformation or cracking due to the mismatch in the thermal expansion between the coating and the substrate. The AE from these localized cracks in the coating may differ from that in the substrate, and this enables a more detailed analysis of the performance of the aluminide coating under tensile stress. AE can thus be used not only to detect cracks but also to monitor their growth and to assess the potential for catastrophic failure, providing valuable information about the durability and reliability of materials like MAR-M247 with an aluminide coating. The ability to track damage evolution in real-time, especially in critical aerospace applications, is one of the key advantages of AE, as it provides immediate feedback that can be used to make decisions about material behavior, design improvements, and failure prevention strategies.

4. Conclusions

AE monitoring has proven to be a highly effective nondestructive evaluation technique for assessing the integrity of aluminide coatings on MAR-M247 nickel-based superalloys under tensile loading. The study demonstrated that AE can reliably detect and characterize damage mechanisms such as crack initiation, propagation, and delamination, providing real-time insights into coating degradation. The distinct acoustic signatures of the coating and substrate failures highlight AE's capability to differentiate between damage sources, offering a detailed understanding of the failure mechanisms. These findings emphasize AE's potential for industrial applications, particularly in the aerospace and energy sectors, where the early detection of coating damage is critical for ensuring component reliability and safety. By facilitating timely intervention and supporting predictive maintenance strategies, AE monitoring enhances the operational efficiency and life-cycle management of high-temperature components.

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