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Thermography assisted mechanical testing of Cold-Spray (AM) repair †

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Abstract: Cold Spray Additive Manufacturing (CSAM) is a solid-state process increasingly used for structural repairs in aerospace and energy sectors. It enables the deposition of dense material at low temperatures by accelerating metal particles to supersonic velocities, thereby reducing thermal distortion. However, the structural integrity of CSAM repairs—particularly at the interface between the deposited layer and the substrate—remains a critical concern. Various post-treatments and characterisation methods have been explored to optimise performance. While X-Ray Computed Tomography (XCT) is effective for sub-surface inspection, it cannot be applied in-situ during mechanical testing. Digital Image Correlation (DIC), a surface-based method, also lacks sub-surface sensitivity. To address this, Infrared Thermography (IRT) was employed alongside DIC during tensile and fatigue testing of aluminium CSAM-repaired specimens. A cooled IRT camera operating at 200 FPS captured thermal data, with Lock-in processing subsequently applied in post-processing. IRT successfully detected early interfacial damage and enabled tracking of crack propagation, which was later confirmed through fracture surface analysis. This extended abstract presents findings from fatigue tests using IRT. Results from DIC and tensile tests will be discussed during the conference presentation.

Keywords: infrared thermography; thermography; cold spay; non-destructive testing; fatigue testing; lock-in thermography.

1. Introduction

Cold Spray Additive Manufacturing (CSAM) has emerged as a promising solid-state technique for structural repair and functional restoration, particularly in aerospace and energy applications where traditional fusion-based processes may compromise substrate integrity. By propelling metal powders to supersonic velocities using heated, pressurised gas, CSAM allows for the deposition of dense, oxide-free layers at relatively low temperatures, preserving the base material's mechanical and thermal properties [1]. This is especially advantageous for relevant defense and aerospace alloys such as Al6061, which are highly sensitive to thermal degradation but show good deposition efficiency and mechanical recovery when repaired via CSAM [2].

A key challenge lies in evaluating the structural integrity of this interface under service-relevant loading conditions. Subsurface porosities, weak bonding, and interfacial cracking are not uncommon and often initiate failure [1]. Non-destructive testing (NDT) methods such as X-ray Computed Tomography (XCT) offer high-resolution volumetric

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data but are limited to pre- and post-test analysis due to geometric constraints and radiation safety.

Infrared Thermography (IRT), particularly when implemented with lock-in post-processing, presents a complementary in-situ technique that is sensitive to local heat generation due to irreversible damage mechanisms such as microcrack formation and interfacial friction. There is enough literature to show its promise in fatigue and fracture investigations of composites and metal structures [3, 4]. This work applies Lock-in IRT during fatigue testing of CSAM-repaired aluminium specimens, with the aim of detecting and monitoring interfacial damage in real-time. Digital image correlation (DIC) and tensile test comparisons will be discussed during the conference presentation.

2. Methodology

Figure 1a shows a schematic of the Cold Spray Additive Manufacturing (CSAM) setup used for repair. High-pressure nitrogen gas (50 bar) is heated to 500 °C and accelerated through a De Laval nozzle, propelling Al6061 powder particles onto the substrate to form the repair layer. Figure 1b shows the geometry and preparation steps for the test specimen. First, a groove was introduced by milling at the surface of a plate to simulate the material removal. Afterwards, the groove was sand-blasted to prepare the surface and CSAM was used to “repair” the plate. Excess of deposit was removed, and the surface was hand-polished before fatigue testing. The repaired region, where the cold spray material (CS) is deposited, is highlighted on the right. It is important to note that as the test was specifically to see the feasibility of the inspection method, more details of specimen manufacturing are beyond the scope of this paper. A servo-hydraulic testing machine with a dynamic range of 200 kN was used for the cyclic loading (fatigue) testing. A load ratio of R = 0.1 was used with a maximum stress of 120 MPa (13.28 kN) at a test frequency of 20 Hz.

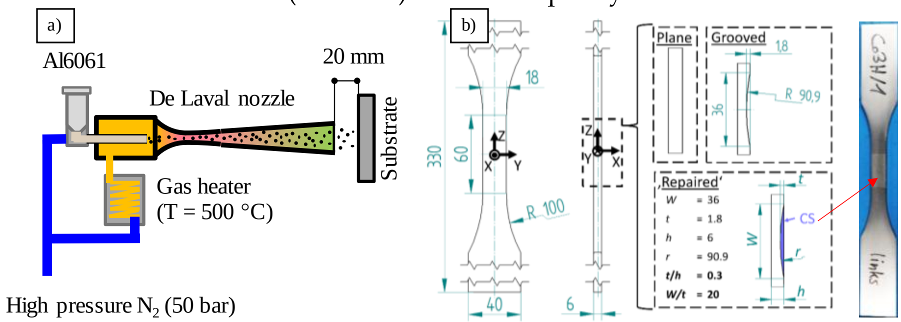

Figure 1. a) Schematic of the CSAM process; b) Design and dimensions for the CSAM test specimen.

For the in-situ inspection, an InfraTec IMAGEIR 9300 infrared camera (MWIR 3-5 µm) was used, with a calibration range of -10 to 60 °C, integration time of 640 µs, and NETD of <30 mK. A 50 mm objective was used, and although the full-frame resolution of the camera is 1280 x 1024 pixels, a custom window of 1120 x 400 pixels was used to avoid unnecessary data storage. The camera was 63.5 cm away from the inspected surface (spatial resolution of 0.21 mm/pixel) and the test surface was coated with LabIR® HERP-LT thermographic paint. Every 2000 fatigue cycles, the camera was triggered to capture 1100 images at 200 frames per second, resulting in a recording time of 5.5 seconds capturing 110 cycles, a schematic is shown in Figure 2a. This is equivalent to 10 images per loading cycle. In addition, a visual camera Baumer VLXT-55.C.I (35 mm Basler Lens C23-3520-5M-P) with a resolution of 2464 x 2048 pixels was used to capture visual images, with one image captured per trigger. A photograph of the experiment setup is shown in Figure 2b. In addition to the test specimen, a reference specimen (also coated) of similar material was placed behind the specimen in the field of view (FOV) of the IR camera (FOVs of both cameras shown in Figure 2c) to capture temperature fluctuations in the environment which could be adjusted during post-processing. As seen in Figure 2c, the visual camera has a larger FOV as compared to the IR camera.

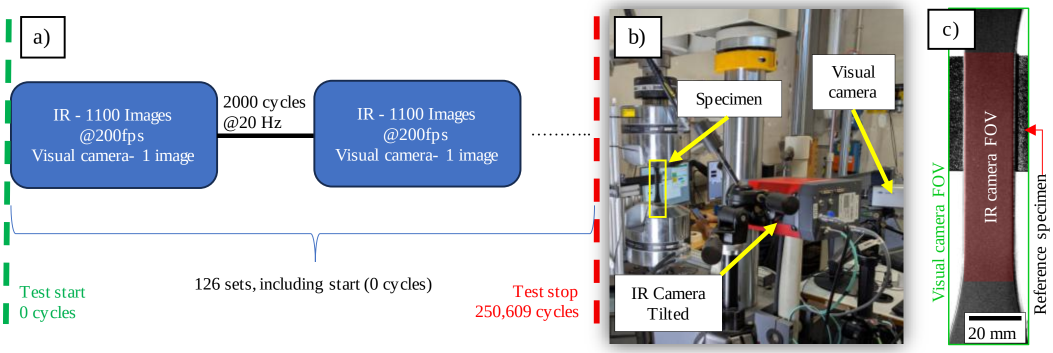

Figure 2. a) Schematic showing how the IR and visual camera were triggered during the tests; b) photograph of the test setup showing the IR and visual camera, along with the specimen; c) photograph obtained from the visual camera, with the IR camera ROI and the reference specimen (behind the specimen relative to the camera) highlighted.

3. Qualitative Results

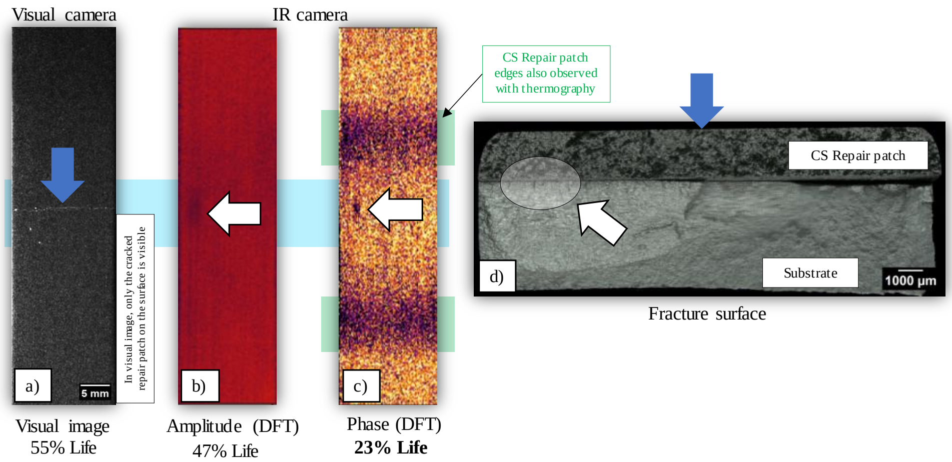

Figure 3. a) photograph from the visual camera of the same FOV as the IR camera at 55% of total fatigue life, with the cracked CSAM repair patch visible; b) amplitude image obtained using DFT of the IR camera data, showing (qualitatively) the first sign of sub-surface damage at 47% of fatigue life; c) similarly obtained DFT phase image of the IR camera data showing sub-surface crack initiation at 23% of fatigue life; d) fracture surface image showing the sub-surface initiation site.

A qualitative analysis is discussed, while a detailed quantitative analysis of the thermal data is presented at the conference and will be published in future journal articles. The specimen was tested until 250,609 cycles until final failure (fractured into two halves). Figure 3a shows a photograph from the visual camera at 55% of fatigue life (approx. 138,000 cycles), when the first sign of visible damage was seen on the surface of the specimen (highlighted with a blue arrow). The cracked CS repair patch, also highlighted with a blue arrow in the fracture surface in Figure 3d, grew within two triggers (i.e. within a period of 2000 cycles). Subsequent tests have been performed with DIC may reveal the onset of damage relatively earlier (to relatively simple visual photography) and will be presented at the conference.

Each trigger signal sent to the IR camera resulted in a set of 1100 thermograms per 2000 cycles. Knowing the fatigue test frequency, Discrete Fourier Transform (DFT) was used to obtain the amplitude and phase signal for each pixel in the thermograms. One amplitude and one phase image were obtained for each set of 1100 thermograms. Retrospective analysis of the images reveals the time (in terms of fatigue life) at which the first signs of damage onset can be detected. Figure 3b shows the DFT amplitude image at 47% of fatigue life or 118,000 cycles, highlighting the first indication of the sub-surface damage that eventually led to final failure (highlighted with a white arrow). This is also forensically evident from the fracture surface in Figure 3d. Figure 3c shows the DFT phase image at 23% of fatigue life or 58,000 cycles, with the same sub-surface damage already visible approximately 70,000 cycles or 28% of the fatigue life before the first visual indication. Also, the CSAM repair patch edges are also visible in the phase image, as they represent a difference in the thickness of the CS repair patch as compared to the central repair region (uniform thickness). Even though relatively simple qualitative analysis already reveals sub-surface damage not otherwise possible with visual inspection, such detection techniques can be further enhanced with quantitative analysis of the DFT signals and will be shown in the presentation.

4. Conclusions

This study demonstrates the potential of Infrared Thermography (IRT), specifically with lock-in post-processing, as a complementary in-situ technique for monitoring interfacial damage in Cold Spray Additive Manufactured (CSAM) repairs. Applied during fatigue testing of Al6061 specimens, IRT enabled early detection of damage initiation and crack progression at the repair–substrate interface. The findings were corroborated through fracture surface analysis, highlighting the reliability of thermal imaging in capturing sub-surface phenomena that conventional methods such as DIC may overlook. These results support the integration of IRT into mechanical testing workflows for CSAM components and lay the groundwork for further research into quantifying damage evolution through thermal signatures.

Author Contributions: Somsubhro Chaudhuri: Conceptualization, Testing, Formal analysis, Visualization, Writing – reviewing & editing. **Sruthi Krishna Kunji Purayil**: Testing, Formal analysis, Writing – reviewing & editing. **Julius Kruse**: Conceptualization, Testing, Investigation. **Mauro Madia**: Conceptualization, Supervision, Writing – review & editing. **Sören Nielsen**: Conceptualization, Investigation, Resources.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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