Robot-based installation of nanostructured metal multilayers on civil infrastructure

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Abstract: Fatigue, particularly in welded joints, causes premature failure of civil infrastructure, an increase in maintenance costs, and safety risks. Nanostructured metal multilayers, applied via electrodeposition, represent a novel treatment to enhance the fatigue strength of welded joints by introducing residual compressive stress during the deposition process, reducing surface roughness and strengthening resistance against extrusions. Nanostructured metal multilayer (NMM) patches may be utilized to postpone crack initiation, restrict the propagation of structural damage, and prolong the life of civil infrastructure. With advancements in robotic technologies, automated robot-based processes may be employed to ensure accuracy and consistency when installing nanostructure patches. In this paper, a methodology for automated robot-based installation of NMM patches on welded joints of civil infrastructure is proposed. Mobile robots, equipped with robotic arms, autonomously navigate to welded joints and install NMM patches using electrodeposition. To validate the methodology, NMM patches are installed and tested under laboratory conditions in small-scale experiments. As a result, integrating NMM technology and robot-based automation, presented in this study, demonstrates a promising approach towards prolonging the lifetime of civil infrastructure.

Keywords: Mobile robots, nanostructured metal multilayers, weld detection, electrodeposition

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1 Introduction

The infrastructure crisis is continuously unfolding. Globally, an increasing number of bridges have reached a critical state, with cracks impairing the structural integrity of steel-based infrastructure. The growing volume of heavy vehicle traffic is identified as a significant factor contributing to the premature aging of bridges. In Germany, the past three decades have seen an increase in freight transport of over 70% [1]. At the same time, 40% of railway bridges are older than 80 years and 40% of motorway bridges are older than 50 years [2], rendering structural health monitoring (SHM) a valuable tool of increasing importance for infrastructure maintenance [3].

Due to increasing traffic, bridges, alongside all other steel-based infrastructure, experience aging, referred to as “fatigue”, with welded connections being the weakest points. To strengthen welded connections against fatigue, post-weld treatments may be applied [4]. As robots have become prevalent in infrastructure inspection and maintenance [5], robots may advantageously be used to apply post-weld treatments on civil infrastructure. In this paper, first results of a post-weld treatment based on nanostructured metal multilayer (NMM) patches on welded connections is presented. Furthermore, a methodology for the installation of the NMM patches in an automated robot-based process on civil infrastructure is described.

The remainder of this paper is organized as follows. In section 2, NMMs and a prototype for installing NMM patches are described. In section 3, a methodology for the robot-based installation of NMM patches is proposed. Section 4 shows validation tests and results concerning the fatigue behavior of NMMs, and the installation of NMM patches under laboratory conditions. Finally, section 5 contains a summary of the paper, conclusions, and potential future work.

2 Nanostructured metal multilayers

In steel-based construction, welded connections are prone to cyclic loading due to intrinsic microstructural and geometrical changes [6]. A coating of Cu/Ni NMM applied on welded seams has been observed to increase the fatigue behavior of welded samples, as published before in [6-8]. Therein, a thin film is electrodeposited on the fatigue susceptible areas of structures, i.e. the welded connections. The film consists of numerous individual Cu and Ni layers, each with a layer thickness of 15 nm and 35 nm, respectively. The NMM is 9 µm thick with a Ni-levelling layer in between the steel substrate and the NMM film. The combination of an increase in mechanical properties due to the Hall-Petch effect [10], which results in a metallically bonded hard coating, inhibiting the formation of persistent slip bands [11], and changing the residual stress states, thus reducing critical notch stresses due to the welding process [12] are thought to be responsible for the effect of the NMM post-weld treatment.

To facilitate the potential of the NMM post-weld treatment, the technology has to be applicable in the field. For civil infrastructure, in specific, the need for a mobile deposition unit for NMM patches is essential, as the demounting of large-scale parts is either not possible or cumbersome and expensive. As a solution, a mobile deposition unit to install NMM patches is developed, which is shown in Figure 1. The essential components of a mobile deposition unit are a container for the electrolyte, the tubing, and the unit capable of performing the deposition. To deploy NMM patches, the mobile deposition unit is pressed onto the welded connection, the chamber is filled with the Cu/Ni sulphate-based electrolyte and by applying the respective current densities in alteration, i.e. 0.45

mA/cm² for copper and 22 mA/cm² for nickel, a NMM is deposited onto the weld seam and its proximity.

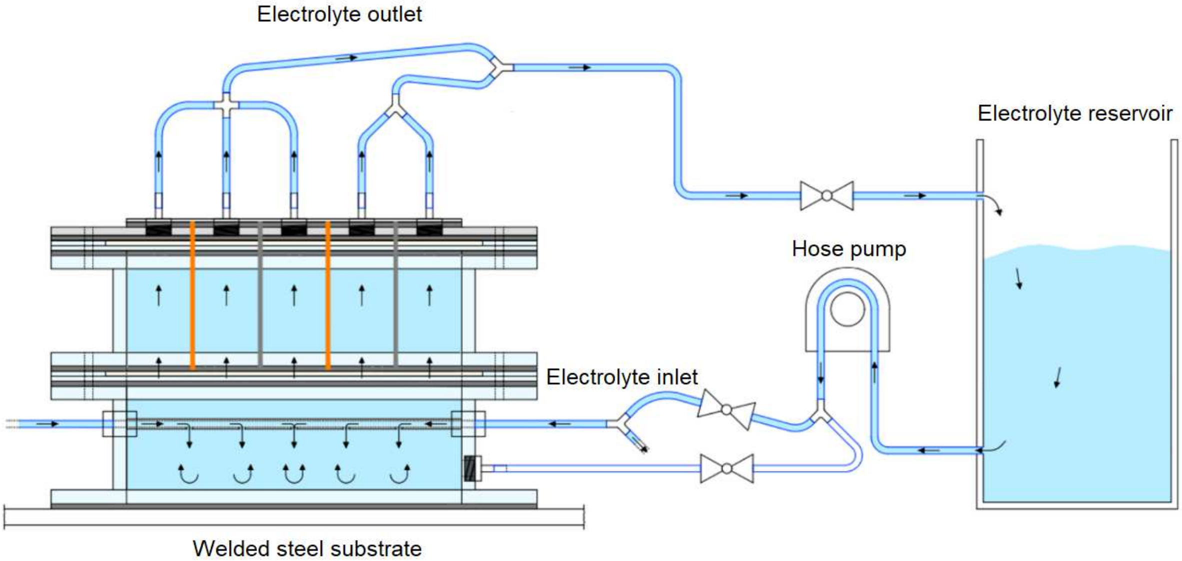


Figure 1: Mobile deposition unit for NMM patch installation.

3 A methodology for robot-based installation of NMM patches

This section describes a methodology to enable automated robot-based installation of NMM patches to welded joints of civil infrastructure using mobile robots. Mobile robots allow autonomous navigation to critical points of civil infrastructure. In this study, the IDOG robotic platform is used as a technological basis [5]. A robotic arm is mounted on the platform with a mobile deposition unit attached to the end effector of the robotic arm. The robotic arm allows fine positioning of the mobile deposition unit to align with the welded joints. To detect the welded joints, a camera is mounted on the robotic arm. An eye-in-hand calibration process [13] is utilized to simultaneously estimate the translation and rotation components of the rigid transformation from the camera frame to the end effector frame. Leveraging state-of-the-art object detection in images using convolutional neural networks [14], welded joints are detected and localized in the images by bounding boxes. Since cameras provide a mapping to a 2D plane (where depth information is lost), a time-of-flight sensor is attached to the robotic arm alongside the camera to measure distances and recover depth information. Upon detection of welded joints, the coordinates of bounding boxes, transformations from the camera frame to the end effector frame, and distance information from the time-of-flight sensor to welded joints allow the computation of full 6 degree-of-freedom (DoF) transformations from the end effector to welded joints. By multiplying the 6 DoF transformations with the current poses of the end effector, the poses of welded joints are computed in the robot-base frames. To enable the installation of NMM patches, the robotic arm is positioned at an installation pose, i.e. at a fixed position from the weld. The installation pose is fed into the inverse kinematics module to obtain goal positions in the joint space of the robot. The robotic arm subsequently moves the mobile deposition unit to the welded joints for the installation of the NMM patches. The tests conducted to validate the methodology are presented in the subsequent section.

4 Validation tests and results

This section shows the validation tests that are conducted (i) to assess the fatigue behavior of NMM patches, (ii) to assess the performance of NMM patches under laboratory conditions, and (iii) to validate the methodology proposed for automated robot-based installation of NMM patches. To evaluate the fatigue behavior of post-weld treatments, different variants of post-weld treatments are tested, as shown in Figure 2. Dogbone samples are prepared in agreement with DIN 50100 [15] in the following configurations: (a) as-welded, (b) machined, (c) high-frequency-mechanical-impact (HFMI) treated, and (d) NMM post-weld treated. A cross-sectional scanning electron microscope (SEM) image and a laminar build-up of the NMM are depicted in (e) and (f), respectively, to highlight the nano-laminate structure of the NMM.

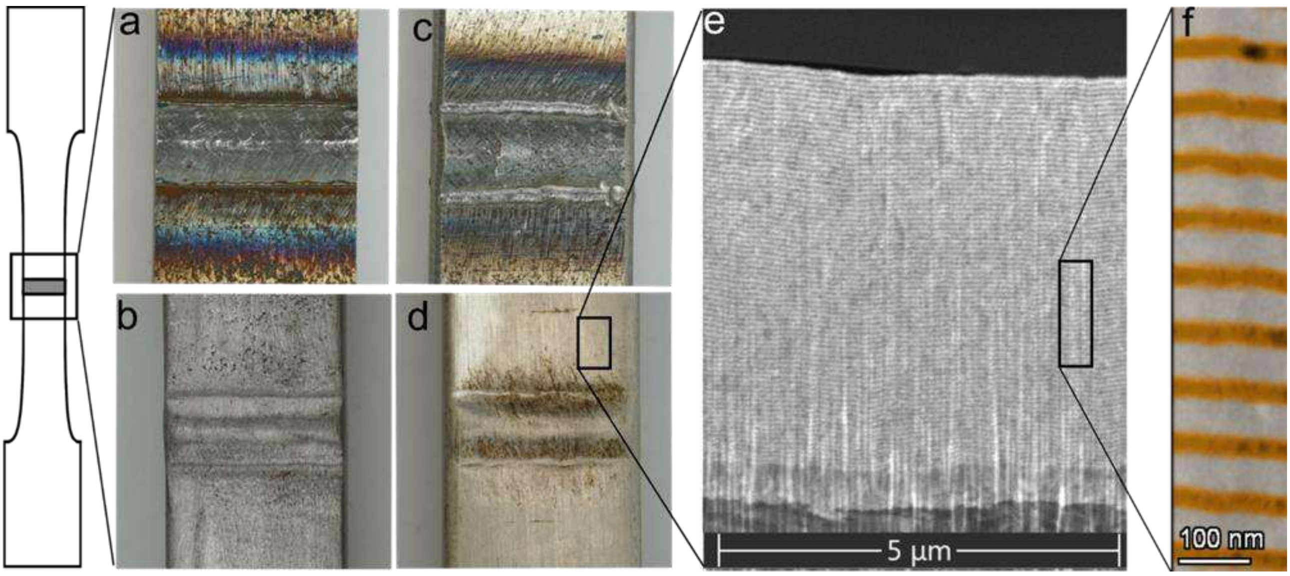


Figure 2: Dogbone sample with welds (a) in the as-welded condition, (b) after polishing the weld proximity, (c) after HFMI post-weld treatment, and (d) after application of the NMM post-weld treatment. (e) Cross-sectional SEM image showing the nanostructured build-up and (f) transmission electron microscopy (TEM) image showing the individual layers highlighted in orange (Cu) and grey (Ni).

Fatigue testing is conducted and evaluated in accordance with DIN 50100 [13]. The results are shown in Figure 3, in which the 5% quantile of the S-N curves are plotted to highlight the substantial change of fatigue strength of the NMM-treated weld in comparison with the as-welded and HFMI-post-weld treated weld; for more details on the results, the reader is referred to [9]. The NMM post-weld treatment shows a superior increase in fatigue strength of the weld compared to HFMI treatment, while ensuring high reliability in fatigue strengthening, which manifests itself in the reduced scatter of results. According to Eurocode 3, the fatigue strength class design parameters for structures under cyclic loading can be read out at N = 2 x 10^6 cycles.

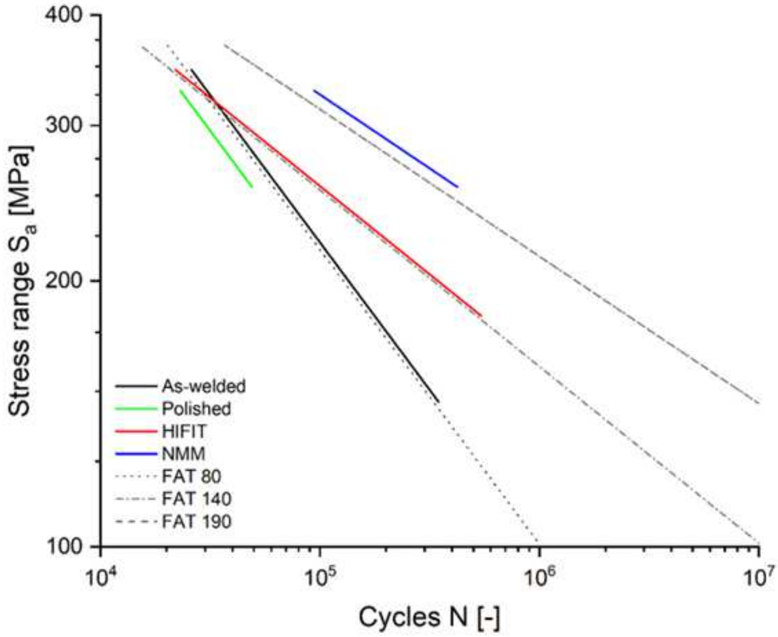
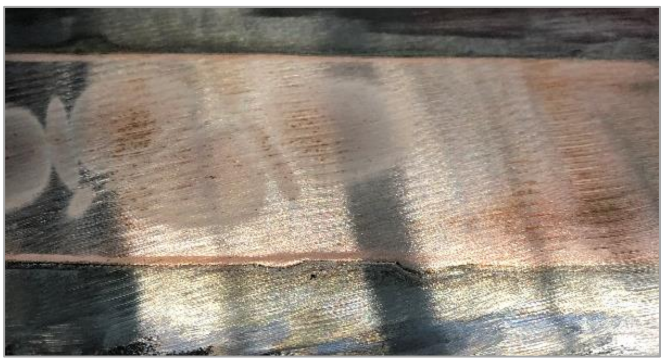


Figure 3: S-N curves of the 5% quantiles compared to the respective design-based FAT classes.

To assess the performance of NMM patches using the mobile deposition unit, an NMM patch is applied under laboratory conditions (Figure 4a). A thorough coating without any flaking, delamination, or other forms of defects can be seen, which is fundamental for the installation of NMM patches in the field. For further analysis, SEM images of the NMM cross section are acquired to gauge the nanoscale application quality (Figure 4b). In Figure 4a, the laminar build-up can be detected, while deviations from the planar coating can be seen. Particularly, in comparison to Figure 2e, the differences are noticeable. Although deviations from the planar coating are visible, no defects such as holes, voids, or delaminations can be found.



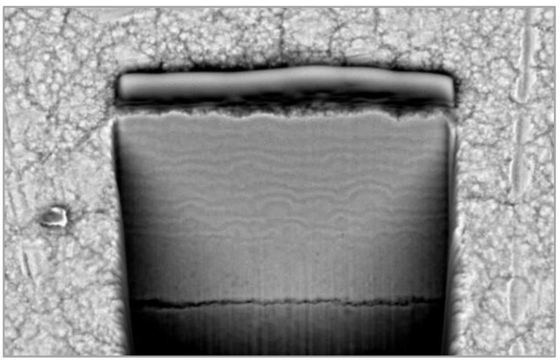


Figure 4: (a) Deposited nanolaminate thin film, (b) SEM image of the NMM cross-section.

Since the prototype of the mobile deposition unit is heavy for the robotic equipment available to the authors, the methodology for automated robot-based installation of NMM patches is tested exemplarily on a small scale. Figure 5a depicts the test equipment, including the IDOG robot with a robotic arm, introduced in [14], as a mobile robot platform, equipped with a robotic arm. A camera and a time-of-flight distance sensor are attached to the robotic arm. The mobile deposition unit, mounted at the end-effector of the robotic arm, is mimicked by a gripper in an open configuration. Details on autonomous navigation of the IDOG using light detection and ranging (LiDAR) sensors and the inertial measurement unit (IMU) are presented in [16].

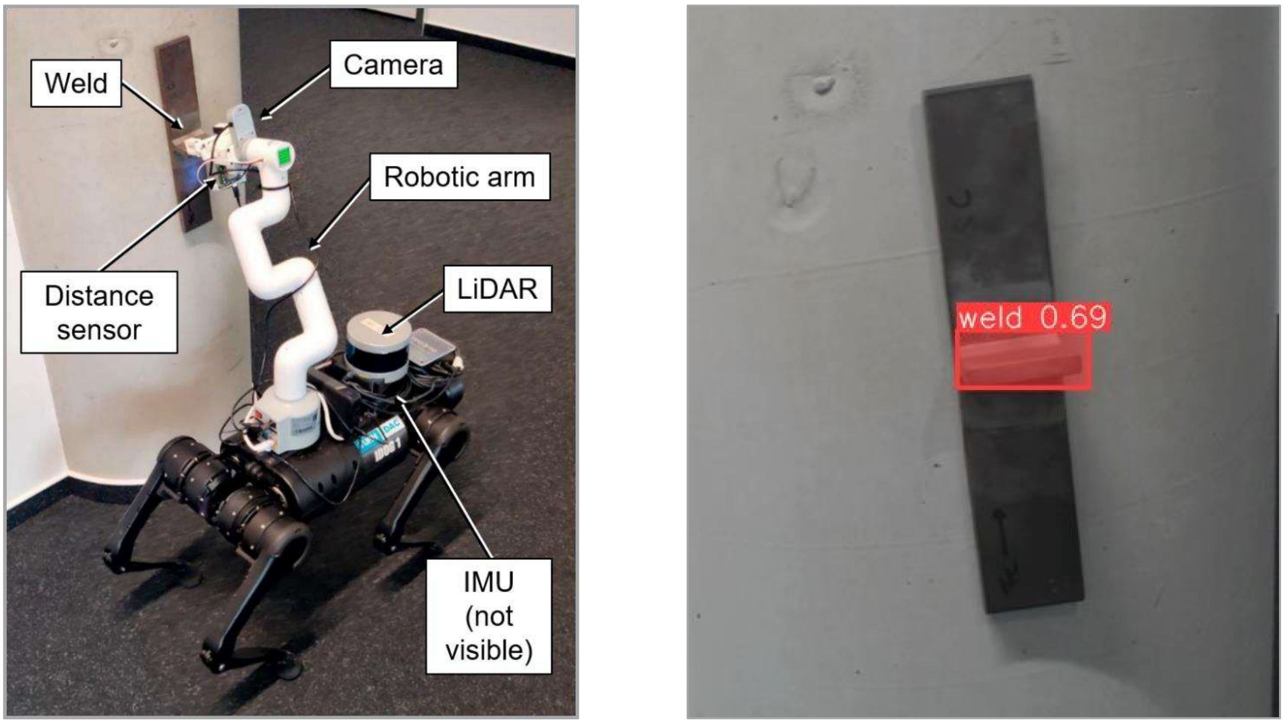


Figure 5: (a) Test equipment and (b) weld detected by the IDOG mobile robot.

To validate the methodology for automated robot-based installation of NMM patches, tests are conducted in an indoor environment with weld samples mounted on concrete pillars that emulate welds on existing civil infrastructure. A mapped environment, as described in [16], is utilized to enable autonomous navigation of the IDOG to goal locations in the vicinity of weld samples. Upon arriving at the goal locations, welds are successfully detected by the IDOG, as depicted in Figure 5b. However, false positives and low confidence scores during weld detection are also observed, indicating the need for a larger and more diverse weld dataset to be utilized for the training of the neural network. Upon detecting a weld, the robotic arm is successfully positioned towards the weld, as shown in Figure 5a.

5 Summary and conclusions

Fatigue, primarily in welded joints, is one of the primary factors that contribute to the failure of civil infrastructure. NMMs applied via electrodeposition may enhance the fatigue strength of welded joints. NMM patches may be installed by automated robot-based processes on civil infrastructure to ensure accuracy and consistency. In this paper, the fatigue behavior of NMM patches have been investigated and tested. A prototype of a mobile deposition unit has been developed to install NMM patches in the field. A methodology proposed to install NMM patches in automated robot-based processes has been investigated and validated. In conclusion, the improvement in the fatigue behavior of NMM patches allows adapting the design of civil infrastructure to either (i) increase the lifetime of structures, while leaving the structures unchanged, (ii) reduce the dimensions of load-bearing components, thereby decreasing material usage, (iii) or a combination of the above. While for bridges, reducing dimensions of load-bearing components is most likely prohibitive, since load-bearing components of reduced dimensions would exacerbate other load cases than fatigue, increasing the lifetime of bridges is of great interest. Furthermore, the results obtained in this study indicate that automated robot-based installation of NMM patches holds significant potential to prolong the lifetime of civil infrastructure. For future installation, a bridge in the harbor of Hamburg has been identified to further improve the approach toward robot-based installation of nanostructured metal multilayers on civil infrastructure.

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