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Procedia Structural Integrity 75 (2025) 193–199

Structural Integrity
Procedia

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Fatigue Design 2025 (FatDes 2025)

Merging nano and macro structure design: Opportunities for the structural integrity of steel infrastructure

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Abstract

Merging the macro-level design with the nano-level design in structural engineering, hence, using the superior properties of nanostructured metallic multilayers for protecting fatigue-critical joints of the macrostructure and ensuring the structural integrity of the steel infrastructure are the objectves of a research effort at TU Hamburg. Nanostructured metallic multilayers (NMM) have significantly higher strength, fatigue resistance and ductility than monolithic homogeneous metal cross sections. The superior structural properties of these nanostructured cross sections are known, and so it is surprising why no attempt has been made to date to use nanostructured cross sections in macro cross sections in structural engineering to improve the cross section properties. This paper links the advantages of nanostructured multilayers with the needs of homogeneous metallic macro-cross sections and examines the question to which extent the high-performance material nanolaminate can compensate for the structural weak parts of metallic infrastructure. The welded joint subjected to fatigue is addressed as vulnerable part of metallic infrastructure. The article provides insights on how nanostructured multilayer can potentially contribute to the future of steel construction, further, how nanostructured multilayer can potentially affect fatigue design. The design as well as the maintenance of cyclically loaded metallic infrastructures, such as bridges and offshore wind turbines, are discussed herein and it is shown how sustainability, resource conservation, reduction of CO_2 footprint, readiness, security of supply and economic viability of steel infrastructure can potentially be achieved.

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Keywords: Fatigue; Design; Metals; Nano; Lifetime; Sustainability; Carbon footprint; Structures

1. A novel post-weld treatment for superior fatigue strength of welded joints

Steel structures age prematurely. Material fatigue, which is caused by cyclic loading and occurs primarily locally in joints, such as welded joints, is particularly important in this context. The weld seam is sensitive to alternating strains due to imperfections in the weld geometry, the material changes in the heat-affected zones caused by the

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10.1016/j.prostr.2025.11.021

welding process and cooling, and the inherent residual stresses. These alternating strains initially lead to extrusions and intrusions, which eventually initiate fatigue cracks and, with sustained cyclic strains, lead to macrocracks. Examples of structures subject to fatigue include steel bridges and offshore wind turbines, particularly the foundation structure, the monopile. In both structures, bridges and monopiles, the welded connections represent the weak points. Fatigue-based design is relatively new: Fatigue-based design of bridge components became part of the standard with the introduction of DIN 18809 in 1987 (DIN 18809, 1987; Geißler, 2014). Accordingly, fatigue damage occurs quite frequently in bridge structures built before 1987. The maintenance and repair costs of a bridge structure per year are estimated to be approximately 1–2 % of the construction costs (Lüesse 1998; Schach et al., 2006). Given a design life of 100 years as targeted by the standard, after 50 years, maintenance costs exceed the original construction costs. Wenzel (2009) reports that Germany only covers about one-third of the necessary costs for the maintenance and repair of bridge structures. The persistent lack of maintenance and insufficient maintenance is noticeable. The reason for the looming infrastructure crisis is the lack of a cost-effective and reliable method for the maintenance and repair of structures subjected to fatigue.

In the offshore sector, the combined effects of fatigue and corrosion have a particular damaging effect and cause the premature failure of structures, components and joints at nominal stress levels that are far below the yield strength of the material. According to Larrosa et al. (2018), the reduction in service life and fatigue resistance is usually due to the premature formation of fatigue cracks in the presence of pitting corrosion. In the bridge sector, fatigue accounts for a large proportion of bridges that have aged prematurely. Fatigue occurs locally and the fatigue-critical details are classified according to the notch catalog of DIN EN 1993-1-9 (2010). A technology that could reliably and economically compensate for the fatigue susceptibility of these notches, and could possibly even be used as a repair method for existing structures, would take infrastructure maintenance to a completely new level. In summary, steel construction reveals needs that are clearly not being addressed using current technology with regard to

- the protection of components and connections subject to fatigue or combined fatigue and corrosion, and
- economical and reliable rehabilitation and repair methods.

This paper discusses to what extent nanostructured metallic multilayers and a technology approach combining the advantages of the nano-cross section with the weaknesses of the macro-cross section can lead to longer-lasting infrastructure with low maintenance and a low CO_2 footprint, and how the length scale bridging fatigue design approach could look like.

1.1. Nanostructured metallic multilayer

Nanostructured metallic multilayers are characterized by material properties that are superior to those of homogeneous monolithic metal cross sections. For example, high strengths (Misra et al., 1998; Clemens et al., 1999; Izadi et al., 2015; Bufford et al., 2012; Nasim et al., 2019), high ductility and fracture toughness (Zhang et al., 2011; Zhang et al., 2014; Mara et al., 2008; Misra et al., 2005; Mara et al., 2010), and high wear resistance (Singh et al., 2012) can be achieved in nanolaminated cross sections.

1.2. Mechanical properties

According to the Hall-Petch relationship, the increase in yield strength due to grain refinement is inversely proportional to the square root of the mean grain size. However, the increase in yield strength as a function of grain size has its limits. For grain sizes < 10 nm, an inverse effect occurs for most metals, and strength decreases with further decreasing grain size (Carlton and Ferreira, 2007).

If the grain size is assumed to correspond on average to the layer thickness when considering nanostructured metallic multilayers (NMM) made of Copper (Cu)/Nickel (Ni), experimental tests show a yield strength of 1150 MPa and 535 MPa for the Ni and Cu layers, respectively, for a grain size and layer thickness of 28 nm (Hansen, 2004). The yield strength of the nanolaminate can be in the order of up to 10 GPa.

In previous studies (Brunow et al., 2020-2023), NMM-treatment, was developed as a new post-weld treatment method of 8 mm thick flat specimens welded with a double-sided V-butt weld. The NMM-treatment is shown in a SEM image in Fig. 1(a).

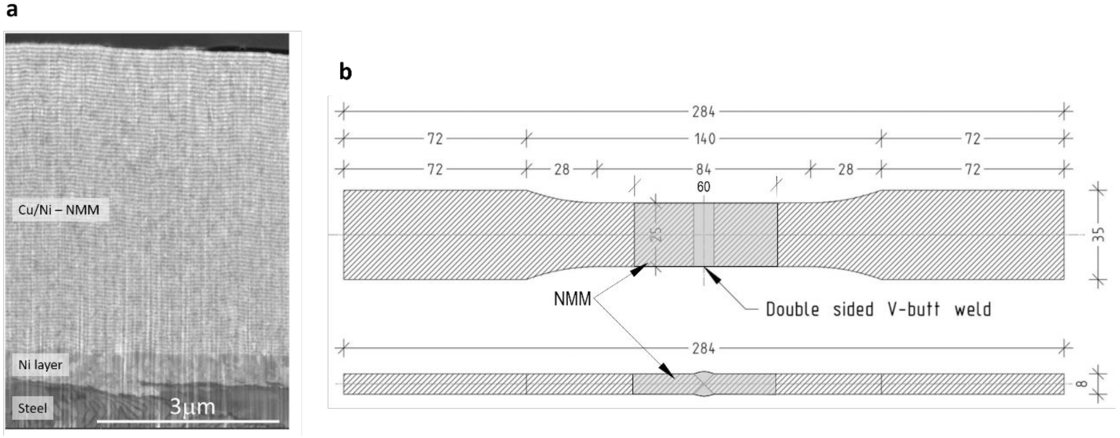

Fig. 1. (a) SEM scan of NMM on steel member; (b) S355-J2 flat sample (dogbone) sample geometry type E acc. to DIN 50125 with centric double-sided V-butt weld and NMM dimensions (Brunow et al., 2023).

How do the excellent material properties of nanostructured metallic multilayers (NMMs) affect the macroscale, i.e., a steel cross-section or a weld seam? Is it possible to specifically leverage the obvious advantages of nanostructured cross-sections to address the weaknesses of macroscale structural engineering, thus compensating for these weaknesses by combining nano and macro scales?

The NMM-treatment consists of alternating Cu and Ni layers. A Ni-leveling layer creates the bond between the steel substrate and the Cu/Ni nanolaminate, as annotated in Fig. 1(a). The potential of nanolaminar cross-sections for structural engineering was first presented in Brunow and Rutner (2020) and Brunow and Rutner (2021). The NMM post-weld treatment has been developed over the last years from small-scale laboratory tests (Brunow and Rutner, 2021; Ramezani et al., 2017) to a scalable technology (Brunow et al., 2022) by using electrodeposition, applicable for new and existing structures (Rutner et al., 2024, Rutner et al., 2025; Spalek et al., 2025, Seidelmann et al., 2025) as well as for metal 3D-printed structures (Falah et al., 2025).

The evaluation of various processes for the production of nanolaminates, including physical vapor deposition, revealed limitations in terms of scalability and transfer to structural engineering. Electroplating using a single-bath process ultimately proved scalable and promising for the production of nanolaminates of any total thickness (Kanani, 2020). A 10 µm-thick NMM was applied to the double-sided V-butt weld seam of an 8 mm thick flat specimen (S355J2) with a geometry according to Type E from DIN 50125 (2022) (Fig. 1b) (Brunow et al., 2023). The NMM-treatment consists of 160 bilayers of alternating 15 nm Cu and 35 nm Ni layers (Fig. 1a). The nanolaminated samples were tested in fatigue tests and compared with as-welded samples. The results show that the NMM-treatment enables a significant increase in fatigue strength from FAT class 80 to beyond FAT class 190. The dominant material mechanism was found to be residual tensile stresses of approximately 1.2 GPa in the NMM and corresponding near-surface residual compressive stresses in the steel component.

The residual tensile stresses arise during the deposition of the nanostructured metallic multilayer (NMM) on the steel surface. Accordingly, residual compressive stresses build up in the steel cross-section as presented by Brunow et al. (2023) and further developed in Spalek et al. (2025). Spalek et al. (2025) combines NMM-treatment with prior clean blasting pre-treatment.

1.3. Residual compressive stresses

The NMM-treatment and prior clean blasting pre-treatment act adjacent to the steel surface, combating material fatigue at its source, the surface. Potential residual tensile stresses present in the welded joints prior to NMM application are suppressed by the residual compressive stresses introduced by NMM and prior clean blasting pre-treatment. The residual tensile stresses generated in the NMM section and the corresponding residual compressive stresses in the steel act across the surface, as schematically shown in Fig. 2(b). The current assumption is that the residual compressive stresses in the steel cross-section form a three-dimensional compressive stress state. This would explain how the measured residual compressive stresses in the steel (S355) can reach values of up to 600–900 MPa, which is significantly higher than the uniaxial yield strength of steel.

A major advantage of the NMM-treatment is that the applied nanostructured metallic multilayer (NMM) does not lead to an abrupt stiffness jump at the edge of the partially applied NMM due to its minor thickness of just a few micrometers. This prevents the edge of the NMM from creating a new fatigue-critical position due to notch effect, as is the case with reinforcement using fiber-metal laminates (Woelke et al., 2015) or carbon fibers (Selvaraj and Madhavan, 2020). It is pointed out that the NMM on the steel section is not contributing in carrying internal forces, but affects only the steel substrate surface by inducing high residual compressive stresses.

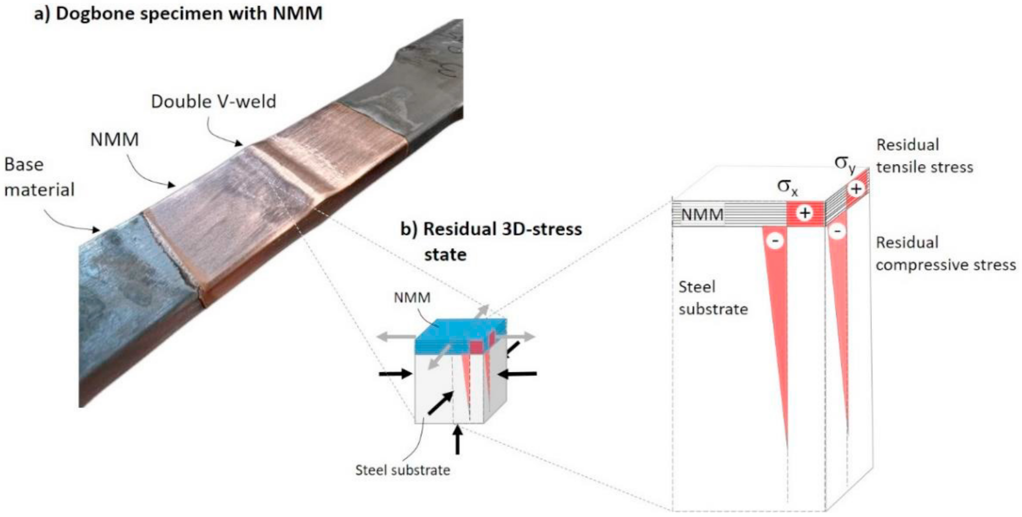

Fig. 2. (a) Dogbone specimen with NMM; (b) Residual 3D-stress state due to NMM-treatment and prior clean blasting pre-treatment.

2. Fatigue design bridging nano and macro lengthscales

An efficient fatigue design should be established to capture the interaction of nano- and macro-cross sections and to realistically assess the effects of NMM on the fatigue strength of the steel joint, as pointed out in Rutner et al. (2024). Extensive fatigue tests are already available for the double-sided V-butt weld joint. Spalek et al. (2025) vary the process parameters and achieve an increase in fatigue strength from FAT 80 to FAT 181 by NMM applied by direct current plating (DC NMM). The application of NMM by pulse current plating (PC NMM) and prior clean blasting pre-treatment, as described in detail in Spalek et al. (2025), even leads to an increase in fatigue strength to FAT 225. Fig. 3(a) presents the S-N diagram of DIN EN 1993-1-9 (2010) supplemented by the S-N curves of corresponding NMM-treated samples using DC NMM and PC NMM, respectively. These thick curves already contain all length-scale bridging information of the effect of the NMM technology on the fatigue-stressed welded joint.

The fatigue assessment of the joint treated with NMM can be assessed as specified in DIN EN 1993-1-9 (2010). Due to the reduced slope of the S-N curve and the significantly increased fatigue strength, a fatigue life that is several times that of the untreated weld seam is achieved, as already described by Brunow et al. (2023) for the NMM-treatment with direct current plating (DC NMM). By further increasing the fatigue strength through optimization of the NMM process parameters and prior clean blasting pre-treatment, as described in Spalek et al. (2025), an up to ten-fold increase in service life is expected. Obviously, these promising results approved for the NMM-treated double-sided V-butt joint must be confirmed for all other notch classes.

Further tests are currently underway to prove whether similar fatigue strength increases also hold for other notch classes. If hyothetically all notch classes are similarly affected by NMM-treatment combined with prior clean blasting pre-treatment, the slope of the S-N curve would not only be dramatically reduced compared to the as-welded condition, but the resulting fatigue strengths would eventually be higher than FAT 160, as shown in Fig.3(b).

DIN EN 1993-1-9 (2010) defines FAT 160 as fatigue strength of the base material. Hence, if the above hypothesis turns out correct, the welded steel assembly treated by NMM technology using pulse current plating (PC NMM) and prior clean blasting pre-treatment would be less fatigue-critical than the base material.

NMM technology is seen applicable across industries, while past studies focused on NMM-treatment of offshore monopiles and of bridges (Brunow and Rutner, 2021; Brunow et al., 2023). NMM has the potential of making fatigue concerns of infrastructure obsolete, extending the service life of infrastructure by a multifold.

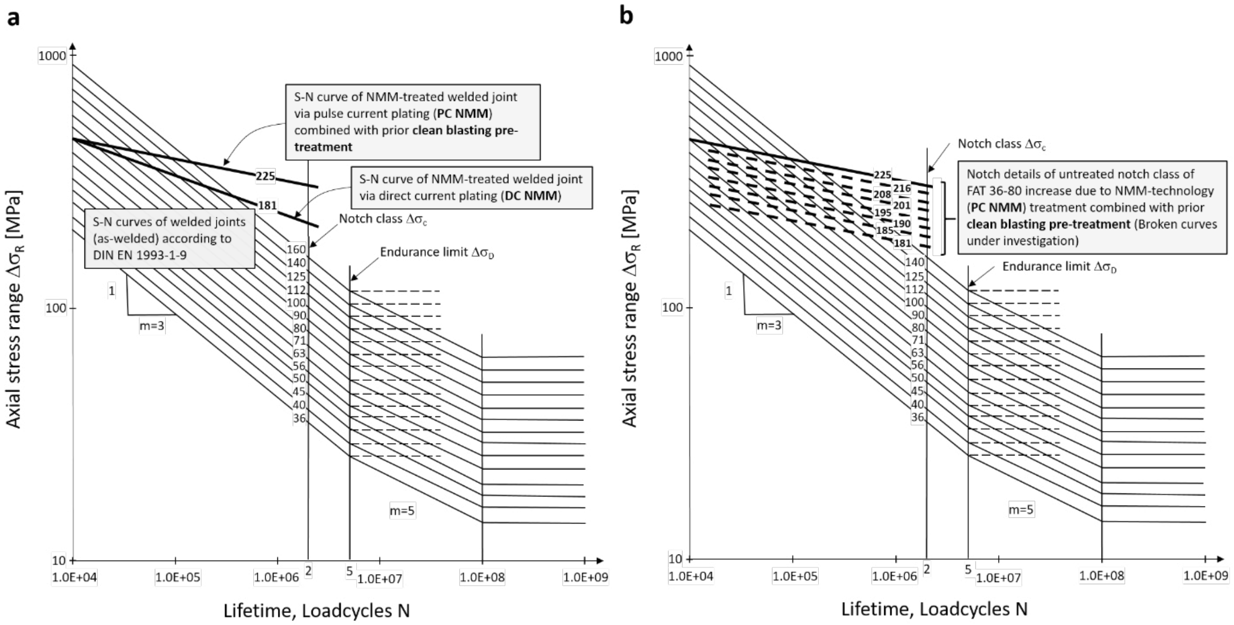

Fig. 3. (a) S-N-curve according to DIN EN 1993-1-9 (2010) and S-N curves of NMM-treated double-sided V-welded connection using DC NMM and PC NMM, where PC NMM is combined with prior clean blasting pre-treatment; (b) Hypothetically assumed fatigue strength increase for all notch classes FAT 36-FAT 80, resulting in FAT 181-FAT 225.

3. Long-term potential of NMM technology

Based on the significant increase in fatigue strength and the narrow scatter of data, as demonstrated for example in Brunow et al., 2023 or Spalek et al., 2025, and assuming that these results are confirmed for all notch classes, this article addresses for the first time the resulting opportunities for civil steel infrastructure.

Sustainability in steel construction, resource conservation, and reduction of carbon footprint

Increasing the fatigue strength of the welded joint by NMM enables a multifold extension of the lifetime of the structure. This means that the service life of infrastructure that is currently experiencing premature aging due to fatigue can be significantly extended. The longer service life postpones the need for new construction, which saves material. Initial analyses of the effects of the NMM technology on potential reduction of CO_2 emissions reveal that the annual carbon footprint of the construction industry can be nearly halved.

Availability and safety of infrastructure

One example in this context are steel structures required for wind farms: The 8th Energy Research Program of October 2023 defines the goal of ensuring resilience and security of supply in the energy system. The short lifetime of offshore wind turbines of 25 years contradicts these goals. This lifetime is limited due to material fatigue, which primarily affects the welds of the supporting structure due to cyclic stress from wave and wind loads. The decommission of wind farms is expected to jeopardize security of supply. Extending the lifetime of monopiles would ensure the availability and security of supply of the energy system.

Economic efficiency of steel infrastructure

The applicability of NMM technology in new and existing bridge structures is expected to extend their service life, thus increasing the economic efficiency. Further, maintenance and repair of NMM-treated welded connections are expected to be significantly more economical than those of untreated welded connections. Findings show that NMMs exhibit very little aging and, in addition to high fatigue resistance, provide high protection against mechanical abrasion.

4. Conclusions

The NMM-treatment causes residual compressive stresses in the steel structural member adjacent to the surface and suppresses existing notches and microcracks. Since the NMM is applied on weld seam, weld toe, and partly on the base material, the induced residual compressive stresses cover all potentially critical areas. This thorough coverage is seen as crucial for achieving the significant increase in fatigue strength of the weld detail. The residual compressive stress is further intensified by using clean blasting pre-treatment prior to NMM-treatment. Initial considerations for a design concept show that the length scale bridging effects of the NMM on the structural steel are captured at the macro level by the S-N curves. Existing fatigue results for the clean-blasted and NMM-treated double-sided V-butt weld joint show an increase from FAT class 80 to FAT class 225 demonstrating that the NMM-treated weld achieves a fatigue strength beyond the base material. Assuming that all notch classes of Eurocode DIN EN 1993-1-9 (2010) experience a comparable increase in fatigue strength, it is conceivable that even the smallest notch class FAT 36 can be increased to about FAT 181, thus placing all notch class above FAT 160 and making the weld no more fatigue-critical than the base material. These assumptions are driven by the promising results of NMM-treatment and prior clean blasting pre-treatment of the double-sided V-butt weld and must be confirmed by appropriate experimental fatigue tests for other notch classes. Further, the respective contributions of NMM-treatment and prior clean blasting pre-treatment to the residual compressive stress increase have to be quantified. The study also explains how the NMM-technology may affect sustainability, resource conservation, reduction of CO_2 footprint, readiness, security of supply and economic viability of steel infrastructure.

Acknowledgements

The authors acknowledge DESY, Hamburg - a member of the Helmholtz Association HGF - for positively evaluating the proposal I-20230348. The authors acknowledge funding of the research project 03EE3105A received by Bundesministerium für Wirtschaft und Klimaschutz (BMWK).

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