metals

Editorial

Editorial Board Members' Collection Series: Improving Structural Integrity of Metals: From Bulk to Surface

Francesca Borgioli [1,*], Denis Benasciutti [2], Umberto Prisco [3] and Tomasz Tański [4]

[1] Department of Industrial Engineering (DIEF), Università di Firenze, Via di S. Marta 3, 50139 Firenze, Italy
[2] Department of Engineering, Università di Ferrara, Via Saragat 1, 44122 Ferrara, Italy; denis.benasciutti@unife.it
[3] Department of Chemical, Materials and Production Engineering, Università di Napoli Federico II, Piazzale Tecchio, 80, 80125 Napoli, Italy; umberto.prisco@unina.it
[4] Department of Engineering Materials and Biomaterials, Faculty of Mechanical Engineering, Silesian University of Technology, 44-100 Gliwice, Poland; tomasz.tanski@polsl.pl
* Correspondence: francesca.borgioli@unifi.it; Tel.: +39-055-275-8734

check for updates

Citation: Borgioli, F.; Benasciutti, D.; Prisco, U.; Tański, T. Editorial Board Members' Collection Series: Improving Structural Integrity of Metals: From Bulk to Surface. *Metals* **2024**, *14*, 1120. https://doi.org/10.3390/met14101120

Received: 6 September 2024
Accepted: 19 September 2024
Published: 1 October 2024

1. Introduction

Metals and alloys continue to play a crucial role in the design and construction of load-bearing structures and mechanical components. Ferrous and non-ferrous alloys find countless applications in various industrial sectors, such as that of automotives, aerospace, the marine sector, construction, and manufacturing.

When it comes to guaranteeing the structural integrity and safety of critical parts, a variety of protection and strengthening mechanisms may be used both at the bulk level and the surface level. At the bulk level, it is possible to take advantage of the correlation between the microstructure and mechanical properties of the material [1]. The chemical composition and content of alloy elements can be controlled to form new alloys or to improve existing ones. Manufacturing processes and heat treatments can be used to tailor the microstructure to possess the desired combination of mechanical properties (e.g., strength, ductility, hardness, and fracture toughness). For example, this can be done by controlling the grain size and/or phase type and distribution. Further, innovative manufacturing techniques, such as additive manufacturing, allow for the fabrication of components with complex geometries and specific mechanical behaviors [2].

Aside from material properties, the subject of structural integrity is also relevant to a variety of topics related to analysis methods [3]. For complex structures, advanced reliability methods and Monte Carlo simulations prove to be efficient tools to assess the probability of failure, and for improving the safety of structures in service [4]. When structures are assembled by welding, the structure integrity is controlled by the fatigue behavior of the welded joints, where high stress concentrations and material inhomogeneities make fatigue cracks more likely to nucleate and grow [5]. Analyses techniques, often supported by finite element calculations, can be carried out by considering the nominal, structural, and local stress or strain, as well as the notch stress intensity factor or fracture mechanics [6]. For structures subjected to tens of millions of fatigue cycles, the structure behavior in the Very High Cycle Fatigue (VHCF) regime is also of interest [7].

In many service conditions, the surface may play a key role in determining the performance and life of a component. Phenomena occurring on metal surfaces, such as wear, wet corrosion, and high-temperature oxidation, may act in synergy with external or even residual stresses, such that a premature failure occurs [8]. Causes of failure, such as corrosion fatigue, stress corrosion cracking, and hydrogen embrittlement, are of major concern in many applications, and many efforts have been made to study their mechanisms in different environments, as well as to model and predict the component behavior.

As a consequence, the modification of the topmost layers of metals and alloys, in order to change their characteristics, has become an important step in the manufacturing of industrial components, with the aim of extending their life. Surface engineering techniques allow us to improve surface hardness, hence wear and fatigue resistance, and corrosion resistance in many environments by means of coating processes [9], such as physical vapor deposition (PVD), chemical vapor deposition (CVD) and thermal spray, as well as diffusion processes [10], such as carburizing and nitriding. Surface engineering treatments, either as a single process or as a combination of different processes, can be tailored to achieve the most suitable characteristics for preserving the structural integrity of components.

The purpose of this Special Issue is to gather articles presenting up-to-date methods and approaches for analyzing, preserving, and improving the structural integrity of metallic components; we also pay attention herein to the phenomena occurring at the bulk and surface level, while also considering the role of the manufacturing process as it correlates to the material microstructure, as well as advanced methods for reliability analysis. The outcomes of experimental, numerical, and theoretical approaches are also considered.

2. Overview of the Published Articles

A total of eleven articles have been published on the structural integrity of metallic components, written from different perspectives, ranging from the bulk to the surface level. Various damage and strengthening phenomena are comprehensively analyzed by means of experimental findings, which are often correlated to the outcomes of numerical and theoretical models. In most articles, uniaxial tensile tests and hardness measurements were used to evaluate the mechanical properties of materials. The Digital Image Correlation (DIC) technique was employed for measuring full-field displacements and strains during testing, while microstructures were analyzed using optical or scanning electron microscopy (SEM). Regarding numerical analysis, several articles took advantage of the finite element method as an efficient tool for assessing the mechanical response and safety analysis of structures with complex geometries. Not only did these articles consider alloys obtained by conventional manufacturing processes, they also included metallic materials and even structures obtained by advanced techniques such as additive manufacturing.

An example of this is provided in the work of Distefano et al. (Contribution 1), who investigated the mechanical properties of Triply Periodic Minimal Surface (TPMS) lattice structures made of Ti6Al4V ELI titanium alloy, and produced via Direct Metal Laser Sintering (DMLS). The mechanical response, elastic modulus, and failure mechanisms of cylindrical lattice specimens with different cell sizes, and subjected to uniaxial compressive tests, were analyzed by means of the DIC technique. The experimental results were also compared with predictions from non-linear finite element models, showing a promising correlation. The study also emphasized how the mechanical response is almost independent of the cell size of the lattice structure.

Titanium alloys were also the focus of the study by Han et al. (Contribution 2), which aimed to improve the mechanical properties of a β-Ti alloy for biomedical applications—namely, a Ti-39Nb-6Zr alloy with different oxygen contents—by means of crystal grain refinement based on recrystallization promoted by specific mechanical and thermal processes. Various microstructural analysis techniques (optical microscopy, X-ray diffraction, field emission scanning electron microscopy (FE-SEM), and electron backscatter diffraction (EBSD)) were used to interpret the findings of the mechanical tests (Vickers hardness, tensile/compressive uniaxial tests). An improvement in mechanical strength in titanium alloys with added oxygen was in fact observed, thanks to the combined effect of solid-solution hardening caused by oxygen addition and crystal grain refinement from static recrystallisation, promoted by a combination of cold swaging followed by solution heat treatments at 900 °C and above.

Methods to inhibit the onset of inhomogeneous plastic deformation (Lüders deformation) in metal forming process are proposed by Qiu et al. (Contribution 3). Besides conventional countermeasures (e.g., interstitial-free steels, plastic pre-strain by skin-pass rolling, bimodal grain size distribution, dual-steels, sandwich-like microstructure, TRIP effect), a new method to suppress Lüders deformation in a medium-carbon tempered martensite steel is proposed. The method promotes simultaneous yielding everywhere, rather than at several local sites, so that the formation of local plastic bands, and thus Lüders phenomenon, are inhibited. The multiplication of yield sites in the steel is achieved by controlling the dislocation density through a suitable heat treatment. The effectiveness of the proposed method was verified on five types of martensite phases with the same morphology, but with different initial dislocation densities obtained by various tempering conditions. The use of DIC allowed monitoring the evolution of the stress–strain field and the elasto-plastic behavior of dog-bone specimens under monotonic tensile testing. The experimental outcomes confirmed the favorable effect of a high initial dislocation density and work-hardening in suppressing the Lüders deformation.

Another study dealing with the improvement in strength of surgical-grade 316L austenitic stainless steels, obtained by microstructure tailoring, is presented by Rybalchenko et al. (Contribution 4). While 316L steel has properties that make it suitable for internal fixation devices in orthopedic surgery, its mechanical properties (e.g., yield strength and fatigue strength) are in fact not as impressive as other alloys also employed in orthopedics. Since 316L steel is a stable material that does not undergo phase transformation during heat treatment and deformation, strategies to increase its mechanical strength could take advantage of grain refinement. Other than by severe plastic deformation, grain refinement could also be achieved by high-pressure torsion (HPT), which triggers a nanocrystalline state in 316L steel. The effect of HPT nanostructuring at two temperatures (20 °C, 400 °C) on a surgical-grade 316LVM austenitic stainless steel (LVM = low-carbon vacuum melted) was evaluated with reference to the microstructure, fatigue strength, corrosion resistance, and in vitro biocompatibility. While the results highlighted the effect of nanostructuring by HPT at 20 °C in enhancing the properties of 316LVM steel for medical use, they also emphasized how additional strengthening through HPT at 400 °C was not fully successful.

Some articles in this Special Issue are more focused on studying aspects of structural design, or their application to engineering case studies. For example, a reliability assessment of an orthotropic steel-deck bridge based on a fatigue crack growth model and finite element analysis, which considers the coupling effect of multiple cracks and the randomness of vehicle loading, is developed by Liu et al. (Contribution 5). In place of time-consuming Monte Carlo simulations, more efficient approaches (such as the iHL-RF and AK-MCS methods) are used to reduce the overall computational time of the reliability analysis. A long-span steel box girder with two U-ribs, subject to random traffic loading, is used as a case study. The stress intensity factor and crack depth of a collinear double crack was calculated using the ABAQUS-FRANC3D interaction technique. The results show that, compared with a single-crack model, the coupling effect of double cracks causes the fatigue reliability of steel decks to decrease significantly. The increase in annual traffic also has a significant effect on bridge reliability. Among the considered sampling techniques, the iHL-RF and AK-MCS methods allow for the computational efficiency to be improved while ensuring the required calculation accuracy.

An application of a Ni–Ti Shape-Memory Alloy (SMA) in the design of a one-touch threaded mechanical coupler, integrated with conventional steel bars in concrete structures, is studied by Song et al. (Contribution 6). The coupler allows for the localized application of SMA bars only in the plastic hinge areas of structural members, where significant displacements occur under seismic loadings. The coupler takes advantage of the recovery properties of SMAs in eliminating the residual deformation in plastic hinge areas. Uniaxial tensile tests on round specimens, supported by DIC, were conducted to analyze the performance of the innovative coupler and the mechanical response of the SMA–steel-connected bar. The experimental results indicate the effectiveness of the proposed mechanical coupler in the localized application of SMA bars within the plastic hinge areas of structural members.

Within the topic of metallic component structural integrity, it is worth mentioning for its relevance the fatigue behavior of welded joints in the VHCF regime (for cycles to failure > 10^7), which is the focus of the review by England et al. (Contribution 7). After describing the ultrasonic testing method, the characteristic course of S-N lines, and the typical crack initiation modes observed in VHCF, the review summarized the literature findings on the fatigue behavior of welded joints for various types of ferrous (low-carbon steel, alloyed steel, stainless steel) and non-ferrous (e.g., aluminum, magnesium, titanium) alloys. Also discussed therein are recommendations provided in design codes released by various organizations for standardization (BS, IIW, AWS, EN, DNV). This is done to emphasize analogies and differences, particularly, regarding the existence of a fatigue limit.

The structural integrity of metal-based components is influenced also by failure phenomena that start at the surface, such as those promoted by corrosion and wear. Therefore, it is very important to study how these phenomena occur, as well as the surface engineering techniques that allow the service life of components to be prolonged, taking advantage of the changes in surface characteristics that occur.

Aluminum alloys are used in many engineering applications because they have an ideal combination of being lightweight with medium strength and good corrosion resistance in many environments. However, when chloride ions are present, as in coastal environments, corrosion phenomena may become severe, and may play a crucial role in reducing the service life of the component. The fracture behavior of aluminum alloys under coastal environmental conditions is reviewed by Alqahtani et al. (Contribution 8). Changes in fracture toughness and fatigue-crack growth rates in coastal conditions are discussed, highlighting the influence of saltwater exposure, humidity, and temperature on fatigue and fracture behavior. Saltwater promotes corrosion, and changes in humidity and temperature affect corrosion behavior. Corrosion phenomena may cooperate in crack initiation and accelerate crack propagation, as in stress-corrosion cracking, corrosion fatigue, and hydrogen embrittlement. Modeling and predictive approaches for estimating the fracture toughness and fatigue crack growth of aluminum alloys, together with their applications and limitations, are also reviewed in their study.

Surface engineering techniques can be used to improve corrosion resistance, as well as surface hardness. Among these different strategies, low-temperature thermochemical treatments have attracted increasing interest in recent years for their surface modification of stainless steels. Traditional nitriding, carburizing, or nitrocarburizing processes, as usually applied to low-alloy steels or tool steels, cannot be transferred directly to stainless steels, since, at the used treatment temperatures, chromium (Cr) compounds can form, prejudicing the corrosion resistance of the alloys. However, by using treatment temperatures so low that nitrogen (N) and/or carbon (C) atoms can easily diffuse, while interstitial (in particular, Cr) atoms can be relatively immobile in the lattice, the formation of Cr compounds is inhibited. In these para-equilibrium conditions, N and C atoms are retained in solid solution in the iron lattices (austenite, ferrite, martensite) beyond the solubility limit, and supersaturated solid solutions, known as "expanded" phases, form. For austenitic stainless steels, low-temperature treatments are known to significantly improve surface hardness, as well as maintaining or even increasing corrosion resistance. The corrosion behavior in different environments of austenitic stainless steels subjected to low-temperature thermochemical treatments is reviewed by Borgioli (Contribution 9). The effects of the presence of N and C on the formation of the passive layers, and on the corrosion behavior of austenitic stainless steels, are considered, and the characteristics of the so-called expanded austenite, or S phase, produced by nitriding, carburizing, and nitrocarburizing treatments are discussed. An analysis of the international literature highlights that the formation of N- or C-rich expanded austenite causes the delay or even inhibition of the occurrence of localized corrosion phenomena (pitting, crevice) in solutions containing chloride-ions. In presence of sulfuric acid solutions, the corrosion behavior is influenced by the microstructure and phase composition of the modified surface layers. The formation of a modified surface layer consisting of only N- or C-rich expanded austenite allows for the maintenance or even increase in corrosion resistance. On the contrary, when N-induced h.c.p. martensite, nitrides, or carbides also form, a significant decrease in corrosion resistance is observed.

Low-temperature plasma carburizing and nitriding were performed by Adachi et al. on AISI 316L stainless-steel tungsten carbide composite layers, which were fabricated using laser metal deposition (Contribution 10). The authors studied the effects of two processes types, single carburizing and continuous nitriding after carburizing. Both treatments were able to produce a supersaturated solid solution of interstitial atoms (C, N) in the expanded and distorted austenite lattice, known as the S phase or expanded austenite. The formation mechanism of this phase was investigated by considering the influence of the carbon, which was present in solid solution in the as-deposited layers, and in eutectic carbides. They observed surface microhardness enhancement of up to about 1365 HV and an improvement in corrosion resistance in a 3.5 wt.% NaCl solution, with a significant reduction in pitting and crevice phenomena, for the treated samples.

Hard coatings are very important for increasing the performance of cutting tools. The synergic effects of nanosecond laser ablation, used as a precision machining ablation technique, and of an AlTiN coating deposited using a PVD technique, are studied by Fang et al. for cemented carbides consisting of WC carbides embedded in a Co matrix (Contribution 11). Also investigated in their study were both the surface integrity, assessed by changes in morphology, microstructure, and roughness, and mechanical integrity, evaluated on the basis of surface Vickers hardness measurements and scratch tests. In most of the sample types, nanosecond laser ablation had a beneficial effect on the mechanical integrity of the coated cemented carbides, as it enhanced surface hardness, and in the scratch tests it reduced the penetration depth and increased the critical load values for the emergence of specific damage/failure events.

Acknowledgments: The Guest Editors wish to thank all of the authors for their high-quality articles, as well as all of the Reviewers for their relevant comments. The Editors have appreciated the support of the *Metals* Editorial Office throughout the publication process.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Distefano, F.; Rizzo, D.; Briguglio, G.; Crupi, V.; Epasto, G. Full-Field Strain and Failure Analysis of Titanium Alloy Diamond Lattice. *Metals* **2024**, *14*, 775. https://doi.org/10.3390/met14070775
2. Han, C.-B.; Lee, D.-G. Effect of Oxygen on Static Recrystallization Behaviors of Biomedical Ti-Nb-Zr Alloys. *Metals* **2024**, *14*, 333. https://doi.org/10.3390/met14030333
3. Qiu, H.; Ueji, R.; Inoue, T. Suppression of Inhomogeneous Plastic Deformation in Medium-Carbon Tempered Martensite Steel. *Metals* **2024**, *14*, 306. https://doi.org/10.3390/met14030306
4. Rybalchenko, O.; Anisimova, N.; Martynenko, N.; Rybalchenko, G.; Tokar, A.; Lukyanova, E.; Prosvirnin, D.; Gorshenkov, M.; Kiselevskiy, M.; Dobatkin, S. Effect of Nanostructuring on Operational Properties of 316LVM Steel. *Metals* **2023**, *13*, 1951. https://doi.org/10.3390/met13121951
5. Liu, J.; Liu, Y.; Wang, G.; Lu, N.; Cui, J.; Wang, H. Fatigue Reliability Assessment for Orthotropic Steel Decks: Considering Multicrack Coupling Effects. *Metals* **2024**, *14*, 272. https://doi.org/10.3390/met14030272
6. Song, M.-K.; Choi, E.; Lee, J.-H. Development and Performance Evaluation of a Mechanical Connection for Steel and Shape Memory Alloy Bars. *Metals* **2024**, *14*, 300. https://doi.org/10.3390/met14030300
7. England, A.; Toumpis, A.; Gorash, Y. Very High Cycle Fatigue of Welds: A Review. *Metals* **2023**, *13*, 1860. https://doi.org/10.3390/met13111860
8. Alqahtani, I.; Starr, A.; Khan, M. Fracture Behaviour of Aluminium Alloys under Coastal Environmental Conditions: A Review. *Metals* **2024**, *14*, 336. https://doi.org/10.3390/met14030336
9. Borgioli, F. The Corrosion Behavior in Different Environments of Austenitic Stainless Steels Subjected to Thermochemical Surface Treatments at Low Temperatures: An Overview. *Metals* **2023**, *13*, 776. https://doi.org/10.3390/met13040776
10. Adachi, S.; Yamaguchi, T.; Tanaka, K.; Nishimura, T.; Ueda, N. Effects of Solid-Solution Carbon and Eutectic Carbides in AISI 316L Steel-Based Tungsten Carbide Composites on Plasma Carburizing and Nitriding. *Metals* **2023**, *13*, 1350. https://doi.org/10.3390/met13081350
11. Fang, S.; Llanes, L.; Guo, Y.B.; Bähre, D. Synergic Effects of Nanosecond Laser Ablation and PVD-Coating on Cemented Carbides: Assessment on Surface and Mechanical Integrity. *Metals* **2024**, *14*, 34. https://doi.org/10.3390/met14010034

References

1. Montanari, R.; Varone, A. (Eds.) *Processing-Structure-Property Relationships in Metals*; Multidisciplinary Digital Publishing Institute (MDPI): Basel, Switzerland, 2019. [CrossRef]
2. Gibson, I.; Rosen, D.; Stucker, B.; Khorasani, M. *Additive Manufacturing Technologies*; Springer: Cham, Switzerland, 2021.
3. Ferri Aliabadi, M.H.; Soboyejo, W.O. (Eds.) *Comprehensive Structural Integrity*, 2nd ed.; Elsevier Ltd.: Amsterdam, The Netherlands, 2023.
4. Kawai, R.; Song, C. Monte Carlo and variance reduction methods for structural reliability analysis: A comprehensive review. *Probab. Eng. Mech.* **2023**, *73*, 103479. [CrossRef]
5. Abdelbaset, H.; Zhu, Z. Behavior and Fatigue Life Assessment of Orthotropic Steel Decks: A State-of-the-art-Review. *Structures* **2024**, *60*, 105957. [CrossRef]
6. Radaj, D.; Sonsino, C.M.; Fricke, W. *Fatigue Assessment of Welded Joints by Local Approaches*, 2nd ed.; Woodhead Publishing Ltd.: Cambridge, UK, 2006.
7. Sakai, T. Historical Review and Future Prospect for Researches on Very High Cycle Fatigue of Metallic Materials. *Fatigue Fract. Eng. Mater Struct.* **2023**, *46*, 1217–1255. [CrossRef]
8. Miller, B.A.; Shipley, R.J.; Parrington, R.J.; Dennies, D.P. (Eds.) *Failure Analysis and Prevention—ASM Handbook*; ASM International: Materials Park, OH, USA, 2021; Volume 11. [CrossRef]
9. Ramezani, M.; Mohd Ripin, Z.; Pasang, T.; Jiang, C.-P. Surface Engineering of Metals: Techniques, Characterizations and Applications. *Metals* **2023**, *13*, 1299. [CrossRef]
10. Czerwinski, F. (Ed.) Thermochemical Treatment of Metals. In *Heat Treatment—Conventional and Novel Applications*; IntechOpen: Rijeka, Croatia, 2012; pp. 73–112. [CrossRef]