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Editorial

High-Performance Applications of Metals and Alloys: Material Properties, Behaviour Modeling, Optimal Design and Advanced Processes

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1. Introduction and Scope

Metals have played an immensely significant role throughout the history of humanity, to the extent that different periods of human development have been marked by the dominance of specific materials, such as the Bronze Age and the Iron Age. Over the centuries, countless discoveries and improvements have been made in the realm of materials, shaping the progress of civilizations. However, in relatively recent times, a notable shift has been observed in the relationship between humankind and metals.

While the growth of human civilization has historically been deeply intertwined with the exploitation of metals, an intriguing transformation has been taking place. The convenience and advantages of metals compared to emerging families of unconventional materials, such as plastics and reinforced composites, are increasingly being questioned. Researchers and technologists have, in recent years, devoted considerable attention to reducing or eliminating metal materials in product design and manufacturing processes in favor of these alternatives.

Despite this movement towards exploring novel materials, metals have not only endured but have thrived even more in our lives. The key to their continued relevance lies in their unparalleled ability to evolve and adapt. This Special Issue takes a closer look at the recent evolution of metals and alloys, highlighting their state-of-the-art applications and solutions that have firmly established metallic materials as successful design solutions thanks to their unique properties.

The present issue is dedicated to exploring the high-performance applications of metals and their alloys, delving into their exceptional material properties, behavior models, optimal use in design, and the cutting-edge processes that drive their advancements.

Metals have long been celebrated for their remarkable mechanical, thermal, and electrical properties, making them the go-to choice for a wide range of high-performance applications. From the aerospace industry, where lightweight yet strong materials are indispensable, to the automotive sector, where the pursuit of fuel efficiency and safety demands innovative solutions, metals continue to play a vital role in shaping modern technologies and engineering marvels.

One of the critical areas of focus in this issue is the in-depth analysis of material properties. Researchers and engineers continually push the boundaries of understanding the fundamental characteristics of metals and their alloys. This includes investigating mechanical properties such as tensile strength, hardness, fatigue resistance, and thermal and electrical conductivity. A comprehensive understanding of these properties is essential in optimizing the performance of metallic materials in specific applications.

Moreover, the behavior models of metals and alloys under various loading and environmental conditions are critical for ensuring the reliability and safety of engineered structures. Advanced modeling techniques, such as finite element analysis and computational simulations, aid in predicting material responses and assist in designing materials that can withstand the challenges of real-world applications.

The optimal use of metals in design is another paramount aspect that this issue seeks to explore. With an ever-expanding array of available materials, selecting suitable metals for a particular application requires careful consideration of cost, performance, and environmental impact. Integrating metals efficiently into the design process can lead to groundbreaking innovations, providing technically superior, economically viable, and sustainable solutions.

In addition to understanding material properties and optimizing their use, this issue also spotlights advanced processes that have revolutionized the production and manipulation of metallic materials. Additive manufacturing, for instance, has emerged as a transformative technology, enabling the creation of complex geometries and customized components with enhanced performance characteristics. Using processes like powder metallurgy and thermo-mechanical treatments, researchers and industries have significantly improved material microstructures and performance.

By shining a light on the high-performance applications of metals and their alloys, this issue aims to showcase the critical role these materials continue to play in shaping the progress of diverse industries. Metals remain at the forefront of technological innovation, whether enhancing the structural integrity of buildings and infrastructure, creating energy-efficient transportation solutions, or advancing medical devices and implants.

Furthermore, exploring novel combinations of metals, such as metal matrix composites and high-strength alloys, promises even greater strides in performance and functionality. The potential applications are limitless, from lightweight materials that enable fuel-efficient transportation to metals with exceptional wear resistance for industrial machinery.

This issue is a platform for researchers, engineers, and industry experts to share their latest findings, innovations, and insights into high-performance metals. By fostering collaboration and knowledge exchange, we hope to accelerate the development of new materials, processes, and design strategies that will shape the future of metals and solidify their position as indispensable elements in the ongoing advancement of technology and engineering.

Via various innovative advancements, metals have managed to maintain their indispensability in crucial sectors of the economy, such as aerospace, automotive, electronics, and construction. Their exceptional strength, malleability, thermal conductivity, and electrical properties have proved instrumental in creating cutting-edge technologies and high-performance products.

The focus of this Special Issue is to shed light on the transformative potential of metallic materials and explore the latest developments that have propelled them to the forefront of modern engineering. It also aims to outline the fundamental trends in the field, showcasing the most recent breakthroughs and applications that have solidified the position of metals in the contemporary landscape of materials science.

From the pursuit of lightweight, high-strength alloys to the integration of advanced manufacturing techniques, the contributions in this Special Issue showcase the endless possibilities that metallic materials offer. By providing an in-depth analysis of their evolution and utilization, this collection seeks to foster further innovations and inspire future research in unlocking the full potential of metals in an ever-changing world.

2. Contributions

The collection includes papers regarding the most multifaced aspects of metals and their alloys as synthesis and treatments [1], experimental characterization [2–4], material models [2,5,6], and engineering applications [7,8], providing a clear cross-section of the wide variety of topics and research arguments under investigation in the scientific community now.

In the case of [1], for instance, the critical importance of surface and subsurface conditions in components and how various manufacturing processes influence them is investigated. As known, the depth of the affected zone depends on the machining operations and process parameters in ways that are not always easy to understand. The study focuses on four process chains involving different workpiece geometries made of AISI 4140 steel (42CrMo4) subjected to heat treatment. The workpieces are further processed using various methods, including grinding, precision turning, laser processing, electrical discharge machining (EDM), and electrochemical machining (ECM). The research aims to understand the resulting surface conditions in these process chains, considering factors like initial material state, residual stresses, microstructure, and hardness distribution. The paper identifies various mechanisms within the AISI 4140 steel due to thermal, mechanical, or mixed impacts during different manufacturing processes. Some mechanisms include work hardening, stress relief, recrystallization, re-hardening, melting, grain growth, and rearrangement of dislocations. Thus, it can be said that the paper provides insights into how different machining processes and the initial material state impact the surface and subsurface conditions of components. It explores the material modifications and the underlying mechanisms responsible for these changes via systematic characterizations and specialized analysis techniques. Understanding these aspects is crucial for optimizing manufacturing processes and ensuring the desired functional properties of components.

The research [2] focuses on thermoelastic modeling at the nanoscale, which becomes increasingly important as devices shrink and heat sources are widely used in modern industries like nanoelectromechanical systems. However, conventional thermoelastic theories are not applicable in high-temperature settings. To address this, the study introduces a novel approach using fractional derivatives proposed by Atangana and Baleanu to describe the thermomechanical behavior of a nonlocal viscous half-space subjected to a cyclic heat source. The viscoelastic properties of the material are assumed to follow the fractional Kelvin–Voigt model, and the impact of small-scale behavior is considered using the nonlocal differential form of Eringen's nonlocal theory. Additionally, the study proposes a generalization of the rule of dual-phase thermal conductivity for thermoelastic materials to include higher-order time derivatives. The numerical results for various physical variables are obtained using the Laplace transform technique. The research performs several in-depth numerical analyses, focusing on the effects of nonlocality, structural viscoelastic indicator, fractional order, higher-order, and phase-lag parameters on the behavior of the nanoscale half-space. The findings indicate that the higher-order terms significantly influence the thermoelastic behavior and can potentially mitigate the impact of thermal diffusion. These higher-order terms also offer a new way to categorize materials based on their thermal conductivities. In conclusion, the research provides valuable insights into thermoelastic modeling at the nanoscale, using fractional derivatives and nonlocal theories. The proposed approach accurately represents materials' behavior under high-temperature conditions, with potential applications in nanoelectromechanical systems and other advanced industries. The findings shed light on the impact of various parameters on the material's response and suggest new avenues for material categorization based on thermal conductivities.

The paper [3] focuses on the metallurgical and mechanical characterization of spheroidal (nodular) cast iron, a commonly used metal alloy with high carbon content in the form of graphite. The correct shape and distribution of graphite nodules are crucial for ensuring the desired properties of the material. The investigation utilizes experimental data from a data mining perspective to extract new and lesser-known information. The researcher employs a machine learning toolkit to apply supervised learners and classifiers (like neural networks, k-nearest neighbors, etc.) to understand the relationship between metallurgical and mechanical features. The method achieves an accuracy rate of over 90%, demonstrating its effectiveness in predicting and analyzing the material's properties. The study sheds light on interesting considerations regarding the dimensional effect on variations in solidification rates, microstructure, and properties of spheroidal cast iron. Understanding these effects can improve control over the material's production process, ensuring its desired performance in various applications. In summary, the paper highlights the importance of graphite nodules in spheroidal cast iron and presents a data mining approach that employs machine learning techniques to analyze the material's metallurgical and mechanical characteristics. The research reveals valuable insights that can aid in optimizing the properties of this alloy for different applications and industries.

In [4], it is investigated the fatigue behavior of thin-walled structures made of AlSi10Mg using selective laser melting (SLM) technology. The specimens with different inner diameter values were subjected to post-process treatments, including T6 quenching, micro-shot-peening, and controlled roughness machining. The fracture data analysis revealed that the mechanical treatments and T6 quenching significantly improved the fatigue strength by over 55% and over 80%, respectively. Microscopic observations were conducted using electron, metallographic, and scanning electron microscopes (SEM). The study concluded that the thickness of the thin-walled structures did not affect their fatigue life in the examined cases.

The behavior of aluminum alloy (AA) structures, particularly AA 5083-H111, which are widely used in engineering applications, is focused by [5]. The researchers employed a Phase–Field Damage Model (PFDM) along with a von Mises plasticity model to accurately simulate the response of AA structures. Uniaxial tensile loading tests were performed on the specimens, and the PFDM was implemented in Finite Element Method software. The plasticity model was extended by modifying the hardening function, resulting in a two-interval approach with linear and Simo-type hardening. The simulation results showed excellent agreement with the experimental force-displacement response. These findings suggest that the AA structures' behavior, including elastic-plastic response and failure by damage, can be successfully simulated and controlled using the PFDM.

The study of [6] deals with thin plates used in engineering applications, which may buckle under compressive loads, especially when combined with lateral loads. Several factors, such as material properties, geometry, support conditions, and imperfections, affect the buckling behavior. The researchers developed a computational model using the Finite Element Method to simulate their mechanical behavior under uniaxial or biaxial compression with lateral loads. The model was verified and validated against the literature's analytical, numerical, and experimental solutions, showing a maximum difference of around 5%. It was then used in a case study involving a simply supported plate with a centered rectangular perforation and subjected to in-plane compressive biaxial load and lateral load. Five metallic materials were considered: AISI 4130 steel, AH-36 steel, spheroidal graphite iron (SGI), compact graphite iron (CGI), and Al 7075-T651 aluminum alloy. The results obtained from the study demonstrate the applicability of the proposed computational model. The biaxial elastoplastic buckling behavior was evaluated, and it was found that plates made of AISI 4130 steel and AH-36 steel achieved the highest ultimate stress and the smallest maximum deflection among the studied cases.

In [7], they examine the life assessment of corroded prestressing wires used in reinforced concrete structures. The objective is to determine the remaining load capacity of corroded wires using the Theory of Critical Distances (TCD). The methodology includes 3D characterization of corroded surfaces, mechanical property evaluation, and Finite Element Analysis (FEA) to model wires with corrosion pits. The developed method allows for a more efficient assessment of the repair range and options for mechanical prestressing systems in various structures. The interdisciplinary approach and state-of-the-art techniques used in the study make it applicable for static and fatigue fracture prediction of prestressed wires. The proposed method also offers a simple and fast way to predict the life assessment of engineering structures, especially for damaged elements with arbitrary geometry features.

The [8] discusses the crawler travel gear, a heavy vehicle propulsion system commonly used in tanks, excavators, and off-road vehicles. Crawler travel gears offer advantages in distributing vehicle weight over soft terrain, but they can also damage paved roads and have complex designs. Due to their significant weight, their reliability must be thoroughly assessed. The main components of the assembly include drive wheels responsible for moving the crawler and the supporting structure holding four-wheel bogies and two-wheel bogies. The paper presents a methodology for Finite Element Method (FEM) analysis of parts of an eight-wheel bogie, following the DIN 22261-2 standard. This analysis aims to determine and verify the structural integrity and performance of the crawler travel gear system.

3. Main Outcomes

The primary information and outcomes discussed in the present issue can be rearranged as follows:

- Forging: Forging is a manufacturing process used to shape and form metals by applying heat and pressure. It has been employed since ancient times to create various mechanical and structural components.
- Metals and Alloys: Metals have played a significant role in human history, with different periods named after prominent materials like the Bronze Age and Iron Age. While metals remain essential to human progress, there is an increasing interest in exploring unconventional materials like plastics and composites.
- High-Performance Metals: The evolution of metallic materials is driven by advancements in various fields, such as nanotechnology, additive manufacturing, and material informatics. Sustainable and multifunctional materials, as well as biocompatible metals, are gaining attention.
- Surface and Subsurface Behavior: The behavior of materials' surface and subsurface conditions is critical for functional properties. Manufacturing processes can modify these conditions and understanding them is vital for designing reliable products.
- Thermoelastic Modeling: Modeling thermoelastic behavior at the nanoscale is crucial as devices shrink and heat sources become prevalent in modern industries. Innovative approaches using fractional derivatives and nonlocal theories are being explored.
- Material Characterization: Material characterization is vital for understanding mechanical behavior, fatigue, and buckling of materials. Computational models, data mining, and machine learning are utilized for accurate simulations and predictions.
- Crawler Travel Gear: Crawler travel gear is used in heavy vehicles like tanks and excavators. It provides advantages in distributing weight over soft terrain but can damage paved roads. FEM analysis and reliability assessments are crucial for their design and performance evaluation.

4. Conclusions and Outlook

While metals and their alloys have been extensively studied for millennia, the interest in them shows no signs of diminishing. On the contrary, it continues to grow.

In particular, there are specific aspects that have garnered considerable attention. However, the mentioned papers only briefly discussed them, highlighting the need for further in-depth exploration.

These aspects include:

- Sustainable Metal Solutions: As the world increasingly prioritizes sustainability and environmental consciousness, developing eco-friendly and recyclable metallic materials has become a crucial area of focus. Researchers and industries strive to create metals with reduced environmental impact, lower energy consumption during production, and improved recyclability, thus ensuring a more sustainable future for metal applications.
- Nanomaterials and Smart Alloys: Nanotechnology has opened up exciting possibilities in materials science, including developing nanomaterials and smart alloys. These cutting-edge materials possess unique properties and functionalities that were previously unimaginable, leading to advancements in diverse fields such as medicine, energy storage, and electronics.

- Additive Manufacturing and Metal 3D Printing: Additive manufacturing, particularly metal 3D printing, has revolutionized industries' utilization of metals. This advanced manufacturing technique allows for complex geometries, reduced material wastage, and rapid prototyping, enabling more efficient production processes and bespoke solutions.
- Very High-Temperature Applications: Metals and alloys have always been favored for their ability to withstand high temperatures in extreme environments. With the growing demand for aerospace, nuclear, and energy-related applications, ongoing research into high-temperature materials and their behavior under extreme conditions remains a critical area of investigation.
- Metamaterials and Metacomposites: Metamaterials and metacomposites are engineered materials with extraordinary properties not found in nature. By carefully designing the structure and arrangement of constituent materials, researchers can create materials with exceptional mechanical, thermal, and electromagnetic properties, promising breakthroughs in various fields, such as aerospace, telecommunications, and defense.
- Biocompatible Metals for Medical Applications: The development of biocompatible metals has significantly impacted the medical field. Titanium and its alloys, for instance, have found extensive use in implants and prosthetics due to their excellent biocompatibility and corrosion resistance, enabling improved patient outcomes and a higher quality of life for many individuals.
- Material Informatics and Computational Approaches: Advancements in material informatics and computational methods have accelerated the discovery and optimization of metallic materials. Using machine learning algorithms and high-performance computing, researchers can efficiently explore vast material databases, predict material behavior, and design tailored alloys for specific applications.
- Multifunctional Materials: The quest for multifunctional materials that can perform multiple tasks simultaneously has led to remarkable achievements in engineering. Examples include shape-memory alloys that change shape in response to temperature, self-healing metals that repair damage, and materials with combined structural and sensing capabilities, opening up possibilities for more efficient and adaptive systems.

These additional points could further enrich the discussion and highlight the dynamic and multidimensional nature of the evolution of metallic materials. The field continues to evolve rapidly, with innovative research and advancements continuously shaping the future of metals in diverse industries and applications.

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