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Editorial

Special Issue on Laser Surface Engineering for Tribology

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1. Introduction

The realm of laser surface engineering has seen continual development, particularly within the realm of tribology, a field dedicated to the examination of friction, wear, and lubrication between interacting surfaces in relative motion. Various laser surface engineering techniques, such as laser surface melting [1,2], alloying [3,4], and cladding [5,6], have been employed to alter material surface properties, enhancing their resistance to wear and friction [7]. Additionally, researchers have delved into the application of lasers to induce nanostructuring on surfaces, aiming to elevate hardness, diminish friction, and augment wear resistance at the nanoscale [8–10]. Concurrently, laser surface engineering has found utility in crafting functionally graded materials [11,12], wherein composition and properties gradually shift across the material's surface, optimizing performance in specific tribological conditions. Furthermore, laser-induced surface texturing [13,14] has garnered attention for its potential to regulate friction and enhance lubrication by creating micro-dimples or patterns on surfaces, thereby influencing contact and sliding behavior. Hence, laser-induced manufacturing holds vast potential applications in the realm of tribology. The combination of laser surface engineering and tribology promises to yield outstanding insights and contributions that illuminate the academic and engineering field.

2. An Overview of the Published Articles

The Special Issue entitled "Laser Surface Engineering for Tribology" includes thirteen papers, featuring a review and twelve research articles. These contributions delve into cutting-edge topics, including innovative preparation methods such as additive manufacturing, preheating, and supersonic-assisted laser deposition. The coverage extends to post-machining techniques and surface texturing, providing a comprehensive exploration of advancements in the field.

Firstly, Zhao et al. (Contribution 1) present a comprehensive review focusing on the laser cladding of aluminum alloys. They believe that laser cladding technology is a highly effective strategy for enhancing the surface hardness and wear resistance of aluminum alloys. This review delves into six distinct types of coatings, namely, Al-based, Ni-based, Fe-based, ceramic-based, amorphous glass, and high-entropy-alloy coatings. The focus is particularly on aspects such as microstructure, hardness, wear resistance, and corrosion resistance. The findings of this work contribute significantly to our understanding of coating design and manufacturing perspectives for aluminum alloys, offering valuable insights for future research and development in this domain.

Reinforcement coating is a common method used to improve tribological properties through laser surface engineering. Ji et al. (Contribution 2) explore laser-clad AlCr2FeCoNiNbx (x = 0, 0.5, 1.0, 1.5, 2.0) high-entropy-alloy (HEA) coatings on Q345 carbon steel, focusing on the impact of Nb incorporation on reciprocating sliding wear resistance. The microstructure evolves from a single Face-Centered Cubic (FCC) solid solution (x = 0) to hypoeutectic and hypereutectic states ($x \geq 1.0$), with increasing Laves

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phase and decreasing FCC. Despite a decline in corrosion resistance, wear resistance improves, and friction decreases with Nb addition. Nb0.5 exhibits remarkably low wear rates, outperforming Nb0 by 3.6 to 7.2 times under different loads. This work demonstrates that introducing Laves-phase-forming elements for hardness modulation could be an effective strategy to enhance the wear resistance of HEA coatings. Rajaei et al. (Contribution 3) discuss the potential of Fe_3Al coatings as an eco-friendly alternative to brake disc coatings. A 500 μm Cr–Mo steel buffer layer is applied to the coating on a gray cast-iron disc to enhance coating quality and prevent hot crack formation. While pin-on-disc tests reveal a coefficient of friction comparable to that of an uncoated disc, the Fe_3Al-coated disc exhibits a significant reduction in particulate matter (PM) emissions. This reduction holds particular importance in light of impending international standards, underscoring the environmental advantages associated with Fe_3Al coatings. The experimental results would be more convincing if standard friction equipment for automobile brake discs was used. Huang et al. (Contribution 4) suggest a laser-clad Ti_5Si_3/Ti_3Al composite coating to enhance the wear resistance of titanium alloys. A double-layer presetting method is employed for the laser cladding using a Ti-63 wt.% Al mixed powder layer and a Si powder layer. The coating predominantly consists of a Ti_5Si_3 primary phase and a Ti_5Si_3/Ti_3Al eutectic structure. The coating's microhardness is approximately 668 HV, more than 3 times higher than the matrix's. Finally, the coating significantly improves the wear resistance of TA2, and the mass wear rate of the coating is less than 1/5 of that of TA2. Liu et al. (Contribution 5) discuss the benefits of in situ NbC-reinforced laser cladding Ni45 coatings, emphasizing their high bond strengths, low dilution rates, small heat-affected zones, and excellent wear resistance. Unlike previous methods using costly pure niobium powder, the authors successfully synthesize NbC in situ in Ni45 powder using affordable FeNb65 and Cr_3C_2. The laser-clad coating is mainly composed of NbC and $Cr_{23}C_6$ phases and exhibits a uniform microstructure and outstanding wear resistance. The coating with 25 wt.% FeNb65 and Cr_3C_2 demonstrates the highest microhardness at 776.3 HV0.2 and exceptional wear resistance, surpassing Cr12MoV steel and the Ni45 coating by about 60 and 24 times, respectively. It provides an attractive strengthening strategy for Ni-based alloys. Zhang et al. (Contribution 6) notice that the CoCrFeNi high-entropy alloy (HEA) is known for its impressive mechanical properties but lacks sufficient wear resistance, particularly under high loads. Their study addresses the limited research on adjusting the deformation mechanism to enhance wear resistance by employing boron doping. The introduction of boron successfully regulates the deformation mechanism, resulting in a remarkable 35-fold improvement in wear resistance for the CoCrFeNi HEA. The authors observe the subsurface microstructure and find a reduction in shear bands and the formation of nanostructured mixed layers, contributing significantly to the enhanced wear resistance. So, this boron doping strategy provides an effective way to improve wear resistance in high-entropy alloys (HEAs).

The post-treatment stage has a strong influence on the mechanical and tribological properties of laser-clad coatings. Zhang et al. (Contribution 7) investigate the post-heat treatment of a laser-clad T15 coating on 42CrMo steel. The microstructural uniformity is enhanced using the author-suggested post-heat treatment in the temperature range of 1100 to 1240 °C. Quenching at 1100 °C results in a lower wear rate, while tempering increases it. During high-temperature quenching, carbides at grain boundaries decompose and integrate into the matrix, while tempering precipitates carbides within the grain. The authors show that heat treatment significantly increases the content of martensite and alloy carbide. The cladding layer's microhardness reaches 910 HV after quenching and 750 HV after tempering. The wear resistance is enhanced by quenching, although no significant change in the friction coefficient is observed.

Machining is another kind of post-treatment for laser additively manufactured parts. Ozaner et al. (Contribution 8) describe the machinability of Inconel 718 (IN718), a widely used Ni-based superalloy in the aerospace, nuclear, and chemical industries, specifically focusing on parts produced through laser metal deposition (LMD). As the machinability of LMDed IN718 has received little attention, this work comprehensively evaluates its machinability in both dry and minimum-quantity lubrication (MQL) cutting environments, considering LMD process variables. The results reveal challenges in machining closer to the substrate due to hardness variations. MQL significantly improves machining, and laser power is identified as a crucial parameter. The study provides practical guidelines for optimizing the machining process and emphasizes the potential economic benefits of MQL in terms of tool longevity without substantial energy cost increase, supporting the successful adoption of LMD in the additive–subtractive hybrid manufacturing of metallic parts.

In recent years, combination with other technologies has been a hot spot in the development of laser processing technology. Utilizing supersonic laser deposition (SLD) technology, Zhang et al. (Contribution 9) explore the fabrication of promising diamond/copper composite coatings for wear-resistance applications. The wettability of Ti-coated diamond is enhanced through optimal parameters in a salt bath. The diamond's surface features nano-spherical titanium carbides, fostering a favorable interface bond with a copper matrix. A protective transition layer acts as a buffer, preventing diamond breakage within the coating. SLD prevents graphitization due to its low processing temperature. The collaborative action of laser and diamond metallization significantly enhances tribological properties, resulting in a microhardness of approximately 173 $HV_{0.1}$, surpassing that of cold-sprayed copper. At a laser power of 1000 W, the diamond/copper composite coating demonstrates low friction (0.44) and a minimal wear rate (11.85 $\mu m^3 \cdot N^{-1} \cdot mm^{-1}$), underscoring SLD technology's substantial potential for creating wear-resistant composite coatings.

Laser power, scanning speed, powder feeding rate, and preheating temperature are important laser processing parameters. Liu et al. (Contribution 10) notice that laser cladding faces challenges on copper due to its high thermal conductivity and reflectivity. The authors explore the impact of preheating temperatures (100, 200, 300, and 400 °C) on laser-clad Ni-based coatings on copper substrates. The microstructures and properties are analyzed, revealing a uniform distribution of Ni-based alloy powder elements, creating good metallurgical bonding. The microstructure consists of cellular, dendrite, and plane crystals, with the main reinforced phases being γ (Fe, Ni), $Cr_{0.09}Fe_{0.7}Ni_{0.21}$, WC, and Ni_3B. The coating preheated at 200 °C exhibits the highest hardness (~942 $HV_{0.5}$) and superior wear resistance and corrosion resistance due to reinforced phases and fine crystals.

Recently, laser-assisted surface texturing has attracted the attention of tribology researchers. Phun et al. (Contribution 11) address the challenge of tool wear due to friction in metal-forming processes and propose a solution through the surface modification of SKH51 tool steel. Using a nanosecond pulse laser with an average power of 25 W, a hexagonal array of micro-dimples is created on the tool surface, facilitating lubricant retention and hydraulic pressure during contact. This work investigates the impact of dimple density and sliding speed on the coefficient of friction through pin-on-disc tests. At a 35% dimple density, the laser-textured surface exhibits a 12.6% lower friction coefficient (0.087) than the untextured surface at a sliding speed of 15 cm s^{-1}. Furthermore, the laser-textured surface shows minimal wear compared to the untextured sample. These findings provide valuable guidelines for tool and die surface treatment, enhancing friction and wear reduction in metal-forming processes. Zhang et al. (Contribution 12) employ laser processing technology to create micro-textures on 42CrMo steel, enhancing the wear resistance in high-load conditions, and particularly addressing tooth plate wear in oil drilling wellhead machinery. Finite element analysis guides the selection of optimal texture shapes and parameters. Three types of textures (micro-dimples, micro-grooves, and reticular grooves) are applied, and dry friction experiments reveal improved wear resistance, with micro-dimples outperforming the other shapes. Specifically, micro-dimples with certain dimensions reduce wear by over 80% in ring-block dry friction. Laser hardening enhances surface hardness, and micro-dimples store abrasive particles, mitigating furrow formation and reducing abrasive wear on tooth plates.

Finally, to resist the tribocorrosion of mild steel in a NaCl-containing solution, Sun et al. (Contribution 13) propose a γ'-Fe_4N nitride layer, which is prepared through plasma nitriding with about 5 µm thickness. At a cathodic potential of −700 mV, the γ'-Fe_4N layer experiences 37% less total material removal (TMR) compared to untreated mild steel, demonstrating resistance to mechanical wear. At an open circuit potential, the TMR is 34% lower, while at an anodic potential of −200 mV, the γ'-Fe_4N layer remarkably reduces the TMR by 87%. This improvement is attributed to the layer's high hardness, corrosion resistance, and ability to resist both mechanical wear and corrosion, reducing wear–corrosion synergism.

3. Conclusions

This Special Issue compiles significant contributions addressing challenges in laser surface engineering for tribology, suggesting a future research focus on application-specific optimization. This involves tailoring laser surface engineering approaches to meet the diverse requirements of various industries, including automotive, aerospace, and manufacturing. Additionally, the utilization of advanced characterization techniques like in situ microscopy and spectroscopy is advantageous for a deeper understanding of dynamic changes in laser-modified surfaces during tribological testing. These proposed research directions aim to further advance laser surface engineering for tribological applications, tackling current challenges and enhancing the practical implementation of these techniques.

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