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Editorial

Advances in Friction, Lubrication, Wear and Oxidation in Metals Manufacturing

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1. Introduction

When quickly reviewing the developments of new materials design and fabrication, and engineering and industrial manufacturing, it was found that tribology is a very complicated and highly challenging field that cannot be avoided to improve the manufacturing cost and increase the material service life.

In recent years, metals manufacturing has been undergoing significant transformation through optimizations of conventional manufacturing methods and systems (casting, forging, welding, etc.) and through the promotion of new manufacturing processes and techniques (advanced rolling, additive manufacturing, nanomanufacturing, etc.), due to the emergence of new materials, such as high-entropy alloys (HEAs), and the growing requirements for manufacturing efficiency and product quality. Simultaneously, tribology, which plays an important role in metals manufacturing, has attracted increasing attention and interest in both the industrial and academic communities. Friction, wear and lubrication between materials or mechanical parts in contacts, and oxidation of engineering materials at high temperatures, are of fundamental importance. However, their multidisciplinary natures are usually underlined in previous research. In general, extensive knowledge about mechanical engineering, manufacturing engineering, contact mechanics, materials science, chemistry and physics is required. With the development of both experimental techniques and computer simulation methods, the origin of friction, principles of lubrication, development and performance of novel lubricants, mechanisms of wear and oxidation for metallic materials and composites during manufacturing processes or under service conditions have become assessable at different length and time scales.

The purpose of this Special Issue is to collect research reports aimed to provide an up-to-date overview and progress in both experimental studies and theoretical investigations on several topics in the field of wear and friction as well as high-temperature oxidation of engineering metallic materials or composites and the development and evaluation of novel lubricants for advanced metal manufacturing or machining.

2. Contributions

In the present Special Issue in *Metals*, eleven research papers with high scientific quality have been published, covering the research topics of experimental characterization of oxidation performance of tool steel for metal rolling industry, evaluation of friction and wear properties of various materials, development of novel lubricants and advanced simulations relevant to the tribological contacts and metal manufacturing.

As one of the most widely applied industrial metal manufacturing techniques to produce bulk products, the rolling process is generally divided into cold rolling process [1,2] and hot rolling process [3,4], depending on the rolling temperatures. For the industrial hot rolling process, high-temperature oxidation of steel work roll and strip and high-temperature friction and wear contact between steel work roll and strips often cause severe problems and affect the surface quality of products [5–7]. Therefore, excellent wear and

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oxidation resistances are generally required for work roll materials to extend the industrial service life of a rolling mill and improve the product surface quality. The article published by Hao et al. [8] aimed to study the oxidation performance of two popular work roll materials, namely indefinite chill (IC) and high-speed steel (HSS), considering the practical environment in the steel hot rolling industry. The authors found that the IC roll material exhibited lower oxidation kinetics in dry air but faster oxidation kinetics in humid air than HSS roll material. In addition, they also observed a large difference in the phase constitutions of the oxidation products between two materials, which resulted in different surface roughness that was believed to affect the roll/steel tribological contacts and cause surface defects, such as scratching and sticking.

Wear performance of a material is largely related to the tribological conditions. An article published by Lee et al. [9] aimed to characterize the friction and wear properties of AISI304 stainless steel under dry, water-lubricated and oil-lubricated tribological conditions. They found that both dry and water-lubricated wear conditions fall in the boundary lubrication regime at a low rotation speed. In contrast, the oil-lubricated wear condition is considered to be near or in the mixed lubrication regime and leads to the formation of a large amount of thin and elongated wear debris. In comparison with the wear tests without lubricant (dry) or with water as a lubricant, the AISI304 stainless steel exhibits a much lower specific wear rate when oil is used as lubricant. Regardless of the lubricating conditions, strain-induced martensitic phase transformation has been found in all stainless steel samples. The wear performance of a material can also be affected by its microstructure. Zhang and co-authors [10] studied the influence of aging treatment on the corrosion and wear resistances of a Ni-Cr-Mo-based C276 superalloy. It was found that the presence of precipitates at grain boundaries due to aging resulted in increases in the friction coefficient, the fluctuations in the friction coefficient during steady-state sliding wear process and also the wear track dimensions. The sensitization degree is also increased with the aging treatment time and severe corrosion occurs.

In order to meet the demands of quick industrial development, the design and fabrication of novel materials with high wear resistance are always required. The study reported by Liu et al. [11] is about mechanical and tribological characterizations of a CoCrFeNiMo high-entropy alloy (HEA), which is a new material concept, different from the conventional alloys, and often has five or more principal elements [12–15]. The authors revealed a large influence of Mo content in the HEA on its wear properties, microstructural features and mechanical loading responses. Both the hardness and abrasion wear resistance of the CoCrFeNiMo HEA were found to be improved when its Mo molar ratio was increased, owing to the solid solution strengthening and precipitation strengthening. The main wear mechanism is severe micro-cutting and delamination when the Mo molar ratio is lower than 1 and changes into severe micro-cutting and micro-fatigue when the Mo molar ratio is increased to 1.5. Li et al. [16] fabricated a Ni-Co-P/Si_3N_4 composite coating with excellent wear properties using Al-Si as a substrate via a pulse-current electroplating process. The electroplated Ni-Co-P/Si_3N_4 coating showed minimum abrasion wear, while the Al-Si substrate showed severe adhesion and abrasion wear in both dry and lubricated conditions. Additionally, it was also noted that the Ni-Co-P/Si3N4 composite coating possessed a hardness of about three-times the Al-Si substrate.

Dong et al. [17] carried out a wear test of steel/titanium under water-lubricated conditions, using black phosphorus (BP) nanosheets as novel lubrication additives. They systematically investigated the influence of BP nanosheet size on the friction and wear responses of a Ti6Al4V alloy during wear contact with GCr15 steel, by adding large BP nanosheet (2–4 μm), medium BP nanosheet (0.3–0.5 μm) and BP quantum dots (6–10 nm), respectively, in the ultrapure water. It was found that all three kinds of BP nanosheets resulted in great reductions in the friction coefficient and specific wear rate compared to pure water, and BP quantum dots were the best lubrication additives. According to their interpretations, the main lubrication mechanisms are ascribed to the BP adsorption film and the tribo-chemical reaction film, which prevent direct contact between titanium alloy and steel counterpart and effectively improve both the anti-friction and anti-wear. An article reported by Benedicto et al. [18] aimed to develop novel sustainable and environmentally friendly alternatives to mineral oil water-based cutting fluids to lubricate and cool during the machining of titanium alloys. They added polyol esters in oil-in-water emulsions and studied the effect of esters' molecular structure as well as the interaction with the metal surface on the formation of lubricant film. Their results revealed an improvement in lubricity by 17% and reduction in tool wear rate by 37%; thus, the newly proposed cutting fluid can be very useful for difficult-to-machine materials to improve the tribological performance and prolong the tool life.

Trzepiecinski et al. [19] focused on the sheet manufacturing of a Ti6Al4V alloy, in terms of a single-point incremental forming (SPIF) experiment and using a grease-free dry anti-friction spray of MoS_2 as the lubricant. They determined the optimal input processing parameters during warm SPIF of a Ti6Al4V sheet with an initial thickness of 0.8 mm based on a split-plot I-optimal design to ensure the maximum formable wall angle. It was found that the tool rotational speed and step size had much more influence on the axial force than the feed rate, while the step size had the most influence on the in-plane SPIF force.

In addition to the experimental techniques, advanced simulation methods, including finite element modeling (FEM) [20,21], molecular dynamic (MD) simulation [22,23] and atomistic-continuum coupled multiscale simulation [24,25], also play very critical roles in the research fields of tribology-related metal manufacturing and friction and wear mechanisms of materials. There are research papers in this Special Issue relevant to these advanced simulation techniques. The first study was reported by Tao et al. [26], which was about a numerical simulation and finite element analysis of shape control characteristics of non-oriented silicon steel for a certain UCMW (universal crown mill with work roll shifting) cold rolling mill. According to their statements, the friction condition between the roll and strip deteriorates due to very large rolling force and the negative shift in work roll shows significant control on the roll gap crown and edge drop. The second study was reported by Zheng et al. [27], which was to investigate the lubrication characteristics of C4-alkance with the addition of iron nanoparticles in the boundary friction system based on a nonequilibrium MD model. A change from sliding friction to rolling friction was found because of the presence of nanoparticles, which acted like ball bearings between two contact surfaces. In addition, their MD simulations also revealed a transition from partial lubrication to full lubrication when the number of C4-alkane molecules was increased. The findings are beneficial to the understanding of the friction phenomenon of a simple lubricant containing nanoparticles within a small confinement. The third study was reported by Zhang et al. [28], which proposed a concurrent multiscale simulation strategy based on the coupling of continuum and atomistic models to study the influence of lubricating conditions (amount of lubricants, contact surface roughness and load) on the three-dimensional contact responses of Al single crystals. In comparison with the pure FEM (not able to capture the accurate information at the atomic scale due to incorrect constitutive law) and MD (very time consuming and having both spatial and temporal limitations) simulations, their multiscale model was validated as very effective in the three-dimensional rough contacts in both dry and lubricated conditions, with significantly reduced computational cost and without sacrificing too much accuracy. When load was increased, the contact area was found to decrease, regardless of lubrication or not. Contribution to load bearing from the lubricant molecules was confirmed by the pressure distribution changes for different loads.

3. Conclusions and Outlook

Research papers published in the "Advances in Friction, Lubrication, Wear and Oxidation in Metals Manufacturing" Special Issue contributed to the update of the state of the art concerning studies on friction, wear and oxidation properties of materials, development and performance of novel lubricants and advanced simulation strategies for friction contacts. The quality and variety of the collected articles are addressed to both academic and industrial researchers who are looking for new information that can contribute to the advancement of future research in these highly challenging research fields.

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