Journal of Tribology

Editorial

Special Issue on Tribology of Additive Manufacturing

Additive manufacturing (AM) enables the rapid fabrication of parts with complex geometries that cannot be easily manufactured with traditional methods. While originally limited to rapid prototyping, recent advances in AM technology also enable direct fabrication of functional end-use parts in, e.g., aerospace, medical devices, and military applications. However, the transition from rapid prototyping to fabricating end-use parts has also revealed technology barriers, including surface quality, accuracy, part variability, and uncertainty about the process–structure–property relationship, to name a few. Crucially, fundamental questions about friction, wear, and lubrication of AM parts have led to substantial research interest in the tribology community. This Special Issue provides significant value to the tribology community by highlighting recent advances of tribology research related to AM, defining the state-of-the-art of tribology knowledge, and framing the challenges and opportunities for future tribology research in this exciting field. It is a collection of 17 research/review papers covering a wide range of state-of-the-art topics in the tribology of additive manufacturing. All the papers have undergone a rigorous and anonymous peer-review process.

Terminologies

Additive manufacturing technology is rapidly progressing and the future may bring many new printing methodologies. However, at present, the AM technology can be broadly grouped into seven categories: binder jetting (BJ), direct energy deposition (DED), material extrusion (ME), material jetting (MJ), powder bed fusion (PBF), sheet lamination, and vat polymerization (VP). Of particular interest is the understanding of the Process–Microstructure–Tribology (PMT) "research hotspot." Table 1 summarizes the topics covered in this Special Issue, in addition to the AM technology and the materials. Furthermore, we categorize the papers into PMT, tribology design, and surface characterization, based on the main topic of the paper. To set the stage, we summarize the contents of the papers per Table 1.

Review Papers

Renner et al. presented a review paper focusing on the corrosion and wear properties of AM-fabricated alloys including steel, titanium, and aluminum. The paper points out that AM-fabricated alloys have better corrosion and wear properties than the casted parts, while the influence of process parameters on the microstructures does not hold true across different additive manufacturing processes and materials. Many other challenges—e.g., anisotropic behaviors, effects of heat treatments, the role of nano-particles, and failure analysis—are recommended for future studies in the field. Also noteworthy is the AM-fabricated metal parts (including PBF and DED) often end up with unique microstructures due to the rapid and repeated heating/cooling cycles and extremely large thermal gradient. Indeed, melting and solidification are highly time dependent and complex processes, making it difficult to simulate and predict. These are areas where more research is needed.

Processing Methods

Sharma et al. presented a literature review on hybrid surface metal matrix composites produced by friction stir processing and provided insight into the PMT relationship. Kang et al. studied the microstructure on the surface, sub-surface, and inner region of a commercial pure Ti part fabricated using laser PBF (LPBF). They indicated that the friction and wear behavior of the three regions are distinct. This is thought to be the consequence of the intrinsic heat treatment induced by the LPBF process. The remelting/heating and recrystallization cause microstructure coarsening and refinement between the three regions.

Post-Processing

Thasleem et al. studied the influence of various post-processing methods such as heat treatment and electric discharge alloying (EDA) on ambient and elevated temperature wear behavior of LPBF AlSi10Mg alloy and compared with the cast parts. Their results indicated that an EDA-treated part has the least wear-rate and coefficient of friction at both ambient and elevated temperatures due to its higher hardness than other samples. Thus, EDA-treating can be considered as a potential post-processing technique.

Table 1 Coverage of the papers in Special Issue

Primary topics	Process–microstructure–tribology relationship (PMT)	Tribology design
Main contents	Review (Renner et al.)	Review: Suh
	Region-dependent microstructures and thermal effects (Sharma et al. and Kang et al.)	Surface texture design: Luo et al., Hoskins and Zou, and Maddox et al.
	Post-processing (Thasleem et al.); reinforced materials (Wang et al., Li et al., and Luo et al.)	Friction-reducing wing structure design (Zhang et al.)
	Rolling contact fatigue performance (Xie et al. and Fasihi et al.)	Friction-controlled morphing surface design (Murashima et al.)
	Metal property predictive platform (Jalalahmadi et al.)	Surface topography characterization (Narasimharaju et al.) hydrodynamic effects (Wagner and Higgs)
AM technology	DED, PBF, ME	VP, ME, MJ, PBF, BJ
Materials	Metals, nylon	Resins, metals

Reinforced Materials

Microstructure reinforcement is also an efficient way to increase wear resistance. Wang et al. studied the effect of TiB_2 content on the microstructure and wear behavior of nano-TiB_{2p}/2024Al composites fabricated by laser DED. Their results revealed that the wear-rate of an 8 wt% TiB_{2p}/2024Al matrix composite with full equiaxed grains is almost 20 times lower than that of the unreinforced alloy due to the grain morphology-induced wear mechanism. Li et al. fabricated a dense Al–Fe–Cr quasicrystal reinforced Al matrix composite using DED. The reinforcement phases contributed to the mechanical mixing layer formation that significantly reduced the coefficient of friction and improved the wear resistance. Luo et al. fabricated short carbon fiber-reinforced nylon using ME and reported that the tribological performance improved.

Applications

Rolling contact fatigue (RCF) is another critical performance for many tribological applications. Xie et al. and Fasihi et al. used laser cladding to enhance the railway rail materials. They showed that by carefully selecting cladding materials, both wear and RCF performance can be improved. However, micro-cracks may initiate from the interface between clad and unclad regions. Jalalahmadi et al. presented a predictive platform for fatigue prediction and AM-fabricated metallic parts qualification. They reported developing an integrated computational materials engineering tool that includes models of crack initiation and damage progression, exploring the design space across geometries and materials.

Design Considerations

Additive manufacturing can also be used to design and process unique functional structures, which may create some breakthroughs in tribological design. Suh highlighted the importance of design in improving the performance of all tribological systems. AM was mentioned as an innovative way to produce a part that is very difficult or even impossible to manufacture using conventional manufacturing while at the same time improve the design quality.

Surface Texturing

There is a large body of tribology literature on the use of surface texturing to reduce the friction and wear characteristics of conventional materials. Surface texturing appears to offer viable flexibility for improving the tribological behavior of AM parts as well. Luo et al. reported that by designing specific surface textures—such as convex squares and triangles, processed via ME—they were able to improve the tribological performance. Hoskins and Zou designed and fabricated a micro-texture inspired by Ocellated Skink using two-photon polymerization (TPP), a VP technique producing nanostructures. They reported that wear was substantially reduced due to the texture through the controlled formation of microcracking. Maddox et al. also used TPP to design and fabricate surfaces inspired by frog toes and applied in the piston ring and liner interface. These designs reduce surface friction by an average of 18% and up to 39%, compared to a flat control. Zhang et al. used VP technology to produce various polygonal three-dimensional patterns inspired by dragonfly wings to identify how the polygonal patterns of the samples with bionic wing veins affected the skin friction. Their study provides insight into the mechanism of flow separation of the dragonfly wing and further improves the structure design. Murashima et al. used VP to design and produce a novel morphing surface that selectively performs as a low-friction or break-like surface. By applying air pressure, the surface switches between a convex and a concave shape, giving a different coefficient of friction. It is worth noting that AM of a part often tends to change a “continuous surface” into many discrete layer boundaries, inducing staircase effects due to the layer-on-layer nature. Narasimharaju et al. systematically investigated the impact of varying surface inclination angles on the build direction on the resultant surface textures. The areal surface texture characterization and particle analysis indicated that the resulted surface topographies are strongly correlated with the surface inclination angles.

Hydrodynamic Effects

Modeling and simulations of the hydrodynamic effects associated with AM processes are also worth investigating. Wagner and Higgs studied the capillary and hydrodynamic effects of the interfacial flow responsible for primitive formation when the binder spreads into the powder bed and forms a bound network of wetted particles in the BJ process.

The collection of articles in this Special Issue represents the active and diverse research efforts in the tribology of additive manufacturing. However, there is still a long way to go in this journey. Fundamental material research, application-oriented research, and novel tribological design are extremely worthwhile and exciting to pursue. We hope this Special Issue on the latest advancements in tribology of additive manufacturing provides insights and stimulates the generation of novel ideas with industrial applications on system diagnosis and machine design for years to come.

Finally, we wish to take this opportunity to sincerely thank all the authors for their scientific contributions. Special thanks also to reviewers for their constructive and insightful comments on all the papers published in this issue.

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