Tribological Behavior of Additively Manufactured Metal Components

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Additive manufacturing (AM) has rapidly become a mainstream method of industrial production. Due to the involved layer-by-layer deposition, the amount of waste material can be limited, drastically reducing overall cost and conserving resources, unlike subtractive methods of manufacturing.

Keywords: additive manufacturing ; 3D printing ; direct metal laser sintering ; tribology

1. Introduction

Additive manufacturing (AM) has rapidly become a mainstream method of industrial production. Due to the involved layer-by-layer deposition, the amount of waste material can be limited, drastically reducing overall cost and conserving resources, unlike subtractive methods of manufacturing [1]. Capable of producing complex, quality components in a matter of hours, metal 3D printing is ideal for rapid prototyping [2]. As AM continues to develop, many sectors seek to scale up their use for end-use component manufacturing. In this regard, metal AM is an ideal method due to its accessibility, low-cost materials, and minimal waste. Furthermore, a vast range of materials, such as titanium-aluminum alloys, stainless steels, and nickel superalloys, can be used to form complex components that could not be made with traditional techniques [2][3]. Titanium, steels, nickel, copper, aluminum alloys, and even gold have all been successfully used in AM processes [4][5][6][7][8][9][10][11][12][13][14]. Aside from the material choice, metal AM processes also allow for improving and tailoring mechanical properties due to the innate optimization opportunities regarding the topology or microstructure design offered by the method [15][16]. As such, metal AM can be utilized to create components with superior mechanical properties compared to traditionally manufactured metal parts [15][17].

The use of metal AM to produce complex and crucial metallic parts becomes increasingly popular due to the unique characteristics of metal AM components. Among these AM-specific attributes are the reduced weight, reduced carbon-footprint, and propensity for part consolidation [18][19]. Also notable is metal AM's potential to create highly complex parts [20]. In traditional metal manufacturing, parts are produced via casting and forging. When utilizing these methods for the fabrication of metal components, the formation of thin walled and irregular shapes becomes particularly difficult [21].

Additionally, AM offers advantages such as design flexibility and the minimization of waste [22]. The most well-known implementation of metal AM in an industrial setting relates to additively manufactured fuel nozzles in GE's Leading Edge Aviation Propulsion jet engine. In this application, powder-based metal AM made the production of a complex component faster while reducing weight by 75% and multiplying the durability five-fold [23].

The most apparent property of AM is a direct result of the layer-by-layer process. Each layer can be as thin as 20 microns, allowing for the fabrication of highly detailed, complex CAD models, a feat difficult to accomplish via the traditional methods of casting or forging [24][25][26]. According to a study conducted by Khaing et al., powder-based AM methods can produce complex metal components, often with finer details than that of traditionally manufactured parts [27]. The strength of metal AM components is also advantageous. It should be noted that the choice of the raw material and the printing parameters have a significant impact on the mechanical properties of metal AM components.

Consequently, metal AM becomes commonplace in industries such as aerospace, architecture, automotive, biomedical, and fuel-cell manufacturing, where its application spans from joint implant fabrication to architectural modeling [28][29]. Though the technology is notable in its current applications, there remains much untapped potential. AM has the potential to reshape the manufacturing supply chain. Components can be printed on demand and the production and distribution of material components can be de-globalized. The carbon footprint of manufacturing could be drastically reduced [30]. While metal AM offers substantial advantages over traditional manufacturing, the layered surface quality presents an obstacle to industry adoption.

In all metal AM processes, material addition is achieved through repeated melting and solidification of raw materials. As a result of the complex cyclic thermal history from heat extraction, melting, and rapid solidification, the surfaces of AM parts feature rather irregular, stochastic surface roughness [18][31]. This stochastic surface topography results in qualities inferior to parts produced via traditional methods [32][33], which currently hinders the efficiency of mechanical AM components.

Significant proportions of energy are lost due to friction in mechanical components, and the lifespan of these components is substantially reduced due to wear [34]. Minimizing friction and wear of metal AM components through tribological assessment is necessary for long-term optimization of the technology for practical use. In practice, consistent mechanical properties, including coefficient of friction (COF), shear strength, and ductility, of AM components are prerequisites for functional application. However, the lack of understanding of the tribological properties of metal AM components, as well as the innately anisotropic nature of layer-by-layer manufacturing, presents a limitation [35][36][37]. Until the surface quality of AM components can be optimized with varying methods, material choices, and post processing technique, traditional techniques cannot be replaced. Typically, as-fabricated metal AM components tend to have a higher COF and are more susceptible to wear due to their irregular surface topography [38].

2. Tribological Behavior of AM Components

Understanding the tribological properties (friction and wear) of metal AM components is crucial for the widespread adoption of this method. In particular, friction and wear performance including the COF and wear rate/volume of metal AM components must be studied. When attempting to accurately measure the tribological properties of components, the common methods are pin-on-disc and ball-on-disk in either linear-reciprocating or rotational sliding tests. These methods, which can be used to characterize wear resistance and wear rates, were vastly used in tests on 316L SLM components [39][40][41][42][43][44][45][46][47][48]. As such, Holovenko et al. tried to mimic bio-inspired surface patterns (gecko's fibrils, dimples, pyramids, mushrooms, mesh, brush, inclined brush) by SLM to assess their effect on friction and wear under unidirectional dry sliding in pin-on-disk configuration. It was shown that SLM can be effectively used to optimize the surface patterns to produce a COF of 0.2, nearly 5 times lower than the flat control sample, with gecko's fibrils, octet-truss, long brush, and inclined brush surface patterns producing the best results [49].

Studies comparing the tribological performance of the metal AM components to traditionally manufactured components have been successfully conducted. In this regard, Bartolomeu showed that 316L stainless steel specimens fabricated by LSM featured better mechanical properties and higher wear resistance compared to hot pressing or conventional casting due to the finer microstructure induced by the process [46]. In high temperature tribological applications, metal AM components have been shown to offer performance advantages. Lester et al. evaluated the tribological performance of AM alloys to arc cladded martensitic steel at 700 °C using pin-on-disc wear tests [50]. Since LMD allowed for fully dense claddings with minimal dilution while maintaining a flawless metallurgical bond, it was found that LMD AM Stellite 6 (a cobalt alloy) outperformed martensitic stainless steel at elevated temperatures. Similarly, Torres et al. studied the tribological performance of abrasion resistant cast iron to LMD Fr-Cr-V alloy components. The AM samples maintained high hardness at temperatures as high as 700 °C, resulting in lower wear compared to traditional cast iron [51][52][53].

Sheng et al. used a mixture of pure nickel, titanium, and silicon powders mixed in a 70N-21Ti-9Si ratio (by wt.-%) to produce a 2.5 mm thick coating on steel substrates via laser-cladding, in which raw material is fused to the workpiece. The study examined the performance of the coatings using dry pin-on-disc testing at elevated temperatures (400–600 °C) against nickel superalloy GH5K. At high temperatures, the 70N-21Ti-9Si coatings displayed an excellent wear resistance, with the wear resistance being 430 times higher than that of stainless steel AISI 304 [53]. By comparing AM coatings to traditional inert gas welded coatings, it was demonstrated that the AM coatings had a Vickers microhardness of 247 HV, 13.3% greater than that of the welding process, which resulted in a 10% reduction of the total volumetric wear loss [54]. This demonstrated that the traditional welding process was more susceptible to wear, namely in the form of micro-ploughing and micro-cutting.

As verified by Prabu et al., the deposition of AlCoCrCuFeNi high-entropy alloy onto Ti-6Al-4V substrates not only improved the resulting mechanical properties but also the resulting friction and wear behavior. Compared to the unalloyed substrate, the high-entropy alloy addition induced a 50 and 260% reduction in friction and wear. Compared to the substrate, the wear mechanism changed for the coated substrate thus only showing minor signs of abrasive wear [55]. The addition of FeCuNiTiAl high-entropy alloys onto Ti-6Al-4V substrates resulted in a 60-fold reduction of the resulting wear rate thus demonstrating the impressive potential of high-entropy alloys to improve the tribological performance [ref]. The observed improvements were traced back to the homogeneous microstructure, the formation of intermetallic phases and solid solution hardening. Similarly, the performance of Al was found to improve with the addition of Al_xCrFeCoNiCu high-entropy alloys with variable Al content applied by laser cladding. Depending on the Al content, the best performance was observed for $Al_{1.5}CrFeCoNiCu$ resulting in a wear rate of 6.6 × 10^{-7} mm^3/Nm [56]. A similar trend regarding the respective wear performance was found for $AlCoCrFeNiSi_x$ high-entropy alloys on AISI 304 substrates [57].

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