Journal of
Manufacturing and Materials Processing

MDPI

Review

Tribological Behavior of Additively Manufactured Metal Components

Raj Shah [1], Nikhil Pai [1], Andreas Rosenkranz [2], Khosro Shirvani [3,*] and Max Marian [4,*]

[1] Koehler Instrument Company, Holtsville, NY 11716, USA
[2] Department of Chemical Engineering, Biotechnology and Materials, University of Chile, Santiago 7820436, Chile
[3] Department of Mechanical Engineering Technology, Farmingdale State College, Farmingdale, NY 11735, USA
[4] Department of Mechanical and Metallurgical Engineering, School of Engineering, Pontificia Universidad Católica de Chile, Macul 6904411, Chile
* Correspondence: khosro.shirvani@farmingdale.edu (K.S.); max.marian@ing.puc.cl (M.M.)

Abstract: Additive manufacturing (AM) has recently become an increasingly popular form of production due to its advantages over traditional manufacturing methods, such as accessibility, the potential to produce parts with complex geometry, and reduced waste. For the widespread industry adoption of AM components, metal AM has the most potential. The most popular methods of metal AM are powder-based manufacturing techniques. Due to the layer-by-layer nature of AM, the mechanical and tribological properties of an additive manufactured part differs from those of traditionally manufactured components. For the technology to develop and grow further, the tribological properties of AM components must be fully explored and characterized. The choice of material, surface textures, and post-processing methods are shown to have significant impact on friction and wear. Therefore, this paper focuses on reviewing the existing literature with an emphasis on the development of advanced materials for AM applications as well as the optimization of the resulting surface quality via post-processing and presents areas of interest for further examination in this prospective technology.

Keywords: additive manufacturing; 3D printing; direct metal laser sintering; selective laser melting; tribology; mechanical properties

Citation: Shah, R.; Pai, N.; Rosenkranz, A.; Shirvani, K.; Marian, M. Tribological Behavior of Additively Manufactured Metal Components. *J. Manuf. Mater. Process.* **2022**, *6*, 138. https://doi.org/10.3390/jmmp6060138

Academic Editors: Hao Wang and Jerry Fuh

Received: 19 October 2022
Accepted: 9 November 2022
Published: 11 November 2022

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 [4–14]. 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 [24–26]. 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 [35–37]. 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].

The state-of-the-art literature regarding the tribological properties of metal AM components largely considers the impact of the specific AM method, material choice, parameter optimization, and post-processing on mechanical and tribological properties. Some review articles focused on specific facets of metal AM, such as energy applications, medical implants, or self-lubricating coatings [1,39–41]. This contribution aims at providing a broad perspective on metal AM methods and at reviewing the existing literature with respect to mechanical and tribological properties of metal AM components as well as at identifying areas, which deserve increased attention and research in the future.

2. Metal AM Methods

In metal AM, the most popular methods are selective laser melting (SLM), direct metal laser sintering (DMLS), and direct energy deposition (DED) [42]. SLM is a powder-based additive manufacturing process that has been in use for several decades [43]. Essentially, a metal component is produced via laser fusion of powdered material [44]. The powdered raw material is either a pure metal powder, such as titanium, or an alloy, such as aluminum silicon alloys (Al-Si). Typically, a basin is filled with raw material before the powder is spread evenly over a build platform to create a level surface. Subsequently, a laser is directed at the platform and scans over a cross section (one layer) of the component. The platform is lowered, and the component is gradually formed in the layer-by-layer method (Figure 1a). In SLM, the lasers used typically operate at temperatures upwards of 660 °C [43].

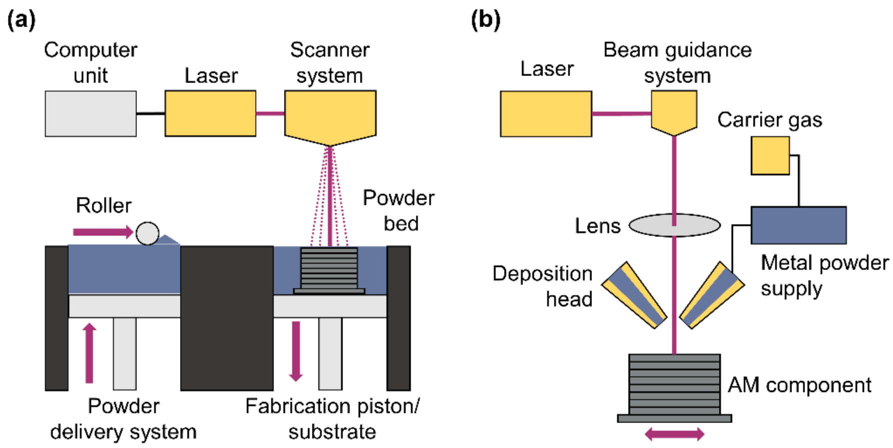

Figure 1. Schematic diagram (**a**) direct metal laser sintering (DMLS) or selective laser melting (SLM) and (**b**) direct energy deposition (DED) processes. Redrawn from [18,45] with permission by CC 4.0.

DMLS also is a powder-based AM method. While it is conceptually similar to SLM, the primary difference between both methods is the temperature of the laser. DMLS lasers reach temperatures of around 610 °C. For both DMLS and SLM processes, ytterbium fiber lasers are typically used. The sintering process consists of heating the metal powder to a temperature at which it partially melts thus causing the material to solidify without complete liquefaction. Overall, DMLS is more versatile since it is compatible with a larger range of materials [43]. It should also be considered that the atmosphere in which the sintering is done can have an effect of sintering density, and can therefore be optimized. One study showed that the influence of the sintering atmosphere is only noticeable when the scan rate is greater than 100 mm/s. Argon atmospheres yielded better densification in comparison to a nitrogen atmosphere, particularly at higher scan rates [46].

DED is similar to the traditional, filament-based fused deposition modeling (FDM) method of AM. FDM functions by moving an extruder head along the x-, y-, and z-axes while extruding streams of molten plastic, which layers the material repeatedly and forms a completed model. DED is similar in that a nozzle extrudes metal powder, while moving around the build platform (Figure 1b). Unlike FDM, in which the filament is heated and then extruded, DED melts the powder after it is deposited using a laser beam. This method is also commonly referred to as laser metal deposition (LMD), laser engineered net shaping (LENS), laser consolidation, or laser cladding [47–49]. DED is popular because of its unique application in component repair (remanufacturing) or coating. The method has been employed effectively with nickel-based superalloys, as well as alloys of cobalt, titanium, and steel [48,49]. Wire arc additive manufacturing (WAAM) also belongs to the DED AM family, utilizing a less-energy consuming heat source compared to laser transmitters or electron beam generators, which makes it economically attractive [50]. Moreover, WAAM can be employed for a wide variety of materials [51–54] without the necessity of a vacuum or inert gas atmosphere. Consequently, this approach is particularly suitable for high reflectivity metal alloys such as aluminum, copper and magnesium due to the higher energy absorption rate [50].

Finally, laser direct metal deposition (LDMD) is also an emerging option [55,56], which has gained notable attention in recent years regarding Al [57] and Ti alloys [58,59] due to the generation of reduced heat-affected zones, minimal workpiece distortions and an excellent surface finish. A general display of the advantages and disadvantages of the most popular methods is presented in Table 1.

Table 1. Advantages and disadvantages of various metal AM processes.

System	Advantages	Disadvantages
Selective Laser Melting	• Little to no constraints in fabrication of complex geometries • Fully melts feedstock	• Requires extensive support materials in most components • High temperature lasers (more energy intensive)
Direct Metal Laser Sintering	• Large range of materials • Lower temperature lasers (less energy intensive)	• Does not fully melt feedstock, so parts may be more prone to mechanical failure than other processes.
Direct Energy Deposition/Laser Cladding	• Suited forrepair/plating • Reduced waste	• Requires vacuum or inert gas to prevent premature oxidation • Support structures cannot be used
Wire arc additive manufacturing	• Suited for repair/plating • Reduced waste • Cost efficiency through high speed and low power consumption	• Complex process controlling • Low forming accuracy with the need for surface finishing as post-processing
Laser direct metal deposition	• Reduced heat-affected zones • Minimal workpiece distortions • Good surface finish	• High equipment costs • Lower process speeds • Requires vacuum or inert gas to prevent premature oxidation

3. Materials of Interest for AM and Their Mechanical Properties

With the use of metal AM rising in popularity, considerable research has been devoted to alloy development. Among the various powdered raw materials, the most studied metal AM alloys are steels as well as Ti-, Al- and Ni-based alloys [60].

Most AM studies involve Ti-6Al-4V alloys. The tensile properties of Ti-6Al-4V AM components are influenced by the microstructure after processing. With an optimized microstructure, SLM Ti-6Al-4V can be engineered to have a greater tensile strength than traditionally manufactured parts [61]. Todai et al. reported that, after parameter optimization, AM components made of Ti-Al alloys can be produced without defects, which are typically found in cast components, thus resulting in better tensile properties and enhanced fatigue behavior [62–64]. The properties of Ti-Al alloys are greatly influenced by oxygen as a stabilizer. Due to the high solubility of O in Ti, there is a great opportunity for tailoring the mechanical behavior of AM parts. Yan et al. reported that the use of oxygen in Ti-Al metal AM components increases strength and minimizes ductility [65]. The overall interest in Ti-Al alloys has led to the development of new Ti-Al alloys, such as Ti-Al-V-Cr and Ti-Al-Mo-V-Cr-Fe [66,67], which are likely to be the subject of increased analysis in future studies. Although being promising for a variety of applications, the main drawback of Ti-6Al-4V alloys is their limited wear resistance. To improve their hardness and wear performance, high entropy alloys have been proven to be suitable coating systems due to their inherent good mechanical properties originating from their homogeneous micro-structure [68–70]. Prabu et al. deposited the AlCoCrCuFeNi high-entropy alloy onto Ti-6Al-4V substrates by laser surface alloying. In this regard, they verified an increased hardness by 300% due to the formation of a predominant bcc phase, solid solution strengthening and the formation of intermetallic phases [71].

Al alloys are the most used alloys in industrial settings, largely due to their high strength-to-weight ratio, corrosion resistance, and ease of casting and forming. Consequently, Al alloys are the subject of increasing interest in AM. Al-(10-12)Si-Mg alloy is the most commonly used Al-based alloy in metallic AM [72,73]. These alloys are relatively easy-to-process using AM due to the low solidification interval and limited thermal expansion [74]. These properties result in near 100% density parts generated by SLM [60]. Similar to Ti-6Al-4V alloys, the deposition of Al-containing high-entropy alloys is an excellent approach to improve the mechanical properties of Al and its alloys. In this regard, Li et al. applied $Al_xCrFeCoNiCu$ high-entropy alloys with variable Al content onto Al. They verified a changing phase situation and, therefore, micro-structure, which correlated with the Al content added. The hardness was improved irrespective of the Al content and demonstrated an increasing tendency with an increasing amount of Al [75].

Iron-based alloys and stainless steels are also used due to their potential for widespread application in the medical industry [76]. 316L, an austenitic stainless steel, is a popular iron-based feedstock, which is known for its high ductility, corrosion-resistance, and strength [67]. In metal AM, 316L samples generally display a higher yield and ultimate tensile strength but tend to show a lower ductility compared to traditionally fabricated components [77]. Yap et al. demonstrated that selective laser melted steel parts are oftentimes stronger but less malleable than casted components [78]. The application of high-entropy alloys has also shown to improve the mechanical and tribological performance of stainless steel [79]. In this context, Liu et al. deposited $AlCoCrFeNiSi_x$ high-entropy alloys onto AISI 304 stainless steel and verified that the resulting micro-hardness linearly correlated with the added Si content. This was traced back to an induced lattice distortion due to the addition of Si. Additionally, the formation of an intermetallic phase was confirmed with increasing Si content [80].

By far, the most promising material subset in metal AM are nickel-based superalloys. They generally feature poor machinability due to low thermal conductivity and high hardness. The innate properties of Ni-superalloys make AM a promising method to develop superalloy components. The popular superalloy Inconel 718 has been used in various metal AM methods, including SLM. The mechanical properties of the additively manufactured alloys are notably superior to cast components but inferior to those of wrought parts [81–83].

It should be considered that the mechanical properties of metal AM components depend largely on the resulting microstructure. Accordingly, research suggests that processing parameters can be optimized for favorable mechanical properties. Critical parameters include laser power, spot size (diameter of the focused laser beam), scanning velocity (speed of laser scan across metal powder), hatch distance (spacing between adjacent scan vectors), and layer thickness [84]. Printing orientation, as well as the optimized design, can further impact the surface morphology of metal AM components, and potentially render post-processing unnecessary [85,86]. For example, Dehoff et al. have shown that adjusting the laser scanning process can influence the grain morphology of Inconel 718 components. However, further research needs to be dedicated to the impact of microstructure tuning on the tribological and general mechanical properties of metal AM components [87]. Facchini et al. considered the ductility of titanium aluminum alloys fabricated by DMLS and found that the AM components were typically half as ductile as cast components. The microstructures of traditional and AM metal components have been shown to impact the mechanical and metallurgical properties of these components [88]. Zhao et al. verified that, in laser metal deposition of the same alloy, the microstructure of the components was responsible for compromised tension and shear strength, as well as a significantly shorter vibration fatigue lifetime [89]. In a comparative study of the properties of DMLS 17-4PH stainless steel and annealed steel components, it was shown that the yield strength of AM components was significantly lower [90]. The rapid melting and solidification of the raw material during DMLS resulted in the formation of a duplex stainless steel, as opposed to the martensite structure of traditionally fabricated components [91]. Likewise, a study of selective laser melted aluminum alloy (AlSi10Mg) verified that the tensile strength and other mechanical properties are significantly improved in AM specimens compared to their cast counterparts, partially due to the fine microstructure developed during SLM [92]. It was, however, noted that SLM-fabricated aluminum alloys were susceptible to metallurgical defects, such as balling, pores, and cracks, which can result in downgraded mechanical properties. A study on the corrosion behavior of forged and SLM processed 316L stainless steel verified that imperfections in the surface of components drastically impact surface degradation [93]. It was shown that forged steel was more susceptible to pitting, while AM steel displayed uniform generalized surface degradation. This can be attributed to the increased porosity of metal AM surfaces. Likewise, it has been shown that the presence of pores in metal AM components heavily impacts fatigue properties and tensile strength, with large pores causing tensile failure [94].

4. 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 [95–104]. 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 (Figure 2), with gecko's fibrils, octet-truss, long brush, and inclined brush surface patterns producing the best results [105].

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 [102]. 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 [106]. 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 [107–109], as shown in Figure 3.

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 [109]. 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 [110]. This demonstrated that the traditional welding process was more susceptible to wear, namely in the form of micro-ploughing and micro-cutting.

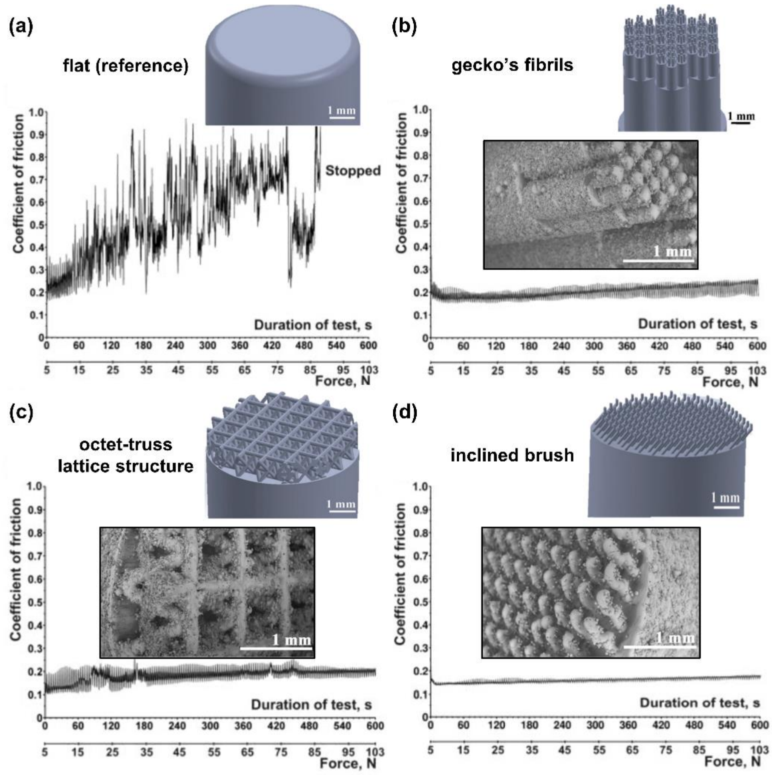

Figure 2. Coefficient of friction versus test duration and normal force of various surface patterns: (**a**) flat (reference), (**b**) gecko's fibrils, (**c**) octet-truss lattice structure, (**d**) inclined brush. Redrawn from [105] with permission.

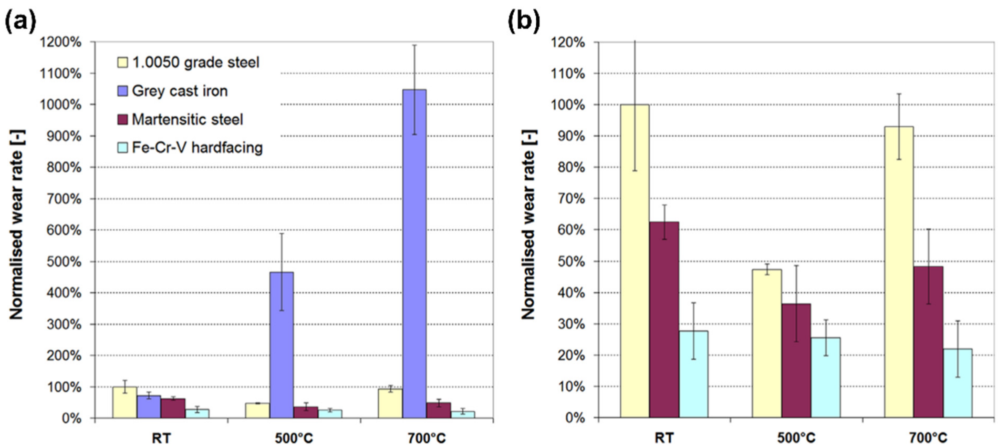

Figure 3. (**a**) Wear rates for various evaluated materials at different temperature normalized on 1.0050 grade steel at room temperature (RT). (**b**) Results after the removal of grey cast iron for better visualization. Reprinted from [107] with permission.

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 [71]. 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 [75]. A similar trend regarding the respective wear performance was found for $AlCoCrFeNiSi_x$ high-entropy alloys on AISI 304 substrates [80].

5. Post-Processing of AM Components to Improve the Tribological Performance

Though metal AM is a promising technology, it is not without its pitfalls. The most common concern with metal AM components relates to their surface quality. As a direct result of the layer-by-layer process, the additively manufactured components are prone to surface irregularities [111]. The solution to this problem relates to post-processing. Through the following methods of surface treatment, the layer roughness can be eliminated. It should be noted that the need for post-processing is the most significant shortcoming of AM. Until an easily accessible and universal method of post-processing is derived, the time and energy required may render the efficiency of metal AM worthless.

One of the common subsets of surface post-processing is material removal. Material removal methods aim to strip a thin layer of material from the surface with imperfections [112]. These treatments can be chemical, mechanical, or laser based. Chemical surface treatments are favorable options in post-processing since they work in all external and internal surfaces of an AM component. Popular methods of chemical treatment are etching [113], brightening, and polishing [114,115]. Generally, an AM component is dipped in chemical baths with variable temperature and duration, depending on the desired amount of material removal.

Laser micro-machining is a common surface treatment. The primary advantage of laser-based treatments is the versatility of material removal based on the optimization of wavelength and pulse duration. The most promising laser-based method is laser polishing, a process in which a laser is passed over the already deposited layer to slightly melt the outer layer (Figure 4). The method can also be utilized during the manufacturing process by passing a laser over each deposited layer to melt any residue before depositing the following layer. This method has been shown to decrease surface roughness of a titanium-aluminum alloy from 4.22 to 0.82 µm [116]. Hackel et al. tested the effects of both shot- and laser-peening on AM stainless steel 316L and found that both methods enhanced the fatigue performance and strength to be superior to wrought material [117].

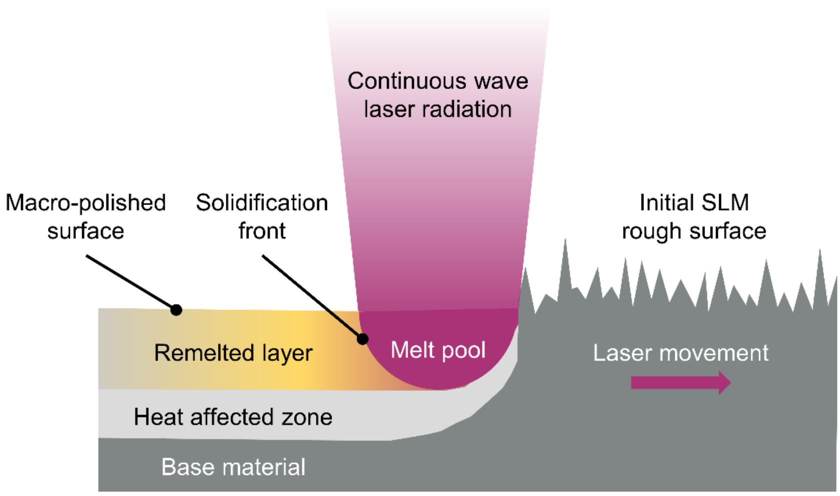

Figure 4. Schematic of laser polishing by remelting a thin surface layer with continuous laser radiation. Redrawn from [118] with permission by CC 4.0.

Mechanical machining is a straightforward method that has been proven effective at reducing the surface roughness of AM components [119]. The processes of polishing, milling, grinding, and tumble finishing have all been shown to be effective post-processing techniques. For Ti-6Al-4V samples, mechanical machining was shown to reduce average roughness from 33.90 to 0.89 μm [120]. Impressive reductions in roughness were also reported with 316L steel samples [121]. Another effective method of post-processing is sand blasting, a process in which sand or other abrasive materials are propelled against the target surface under high pressure. When used on aluminum-magnesium samples, the method successfully reduced the surface roughness, while increasing surface hardness [122]. Mechanical machining methods have also been shown to improve fatigue strength by 30–50%. Sagbas et al. tested the effects of sand blasting and shot peening on DMLS manufactured AlSi10Mg parts and found that post-processed samples had a reduced surface roughness and increased hardness, resulting in significantly lower specific wear rates [123].

Besides subtractive post-processing methods, mechanical treatments such as rolling are commonly used. Rolling is a method used to induce plastic deformation by pressing a roller against the surface of the material. Rolling has been successfully used on DED components [124–127]. Overall, the use of these post-processing techniques is an exceptionally effective solution to the inherently low surface quality of metallic additively manufactured parts, and results in dramatically lower roughness values. Sagbas et al. found that surface roughness of AM components drastically affected the tribological behavior of the samples. After treating samples with various post-processing methods, it was shown that polished samples with a low roughness value had a COF of 0.0563, while shot blasted samples with high roughness values had nearly double the COF (0.1356) [123]. A study by Ye et al. examined the effects of various post-processing methods for AM metals, such as hot isostatic pressing, shot peening, and laser polishing [128], see Table 2.

Table 2. Summary of effects of post-processing effects on AM metals [128].

Post-Processing Method	Effect on Surface Finish	Effect on Porosity	Microstructure Changes
Laser polishing	Improves surface finish	Decreases porosity in the near-surface region	Refines the grains
Heat treatment	n/a	n/a	Decreases defect density and increases microstructure stability
Hot isostatic pressing	Increases surface roughness	n/a	Produces refined grains and high-density dislocations
Laser shock and shot peening	Increases surface roughness	n/a	Refines the grains

6. Outlook and Conclusions

As metal AM develops, industrial sectors are eager to scale up their use of the technology. With 3D printing potentially being an economically and mechanically advantageous option for the fabrication of complex metal components, interest in the aerospace, automotive, and biomedical industries continues to grow. For the technology to develop further, the tribological and mechanical properties, post-processing techniques, and raw materials must be critically analyzed and carefully improved to meet industrial needs.

The mechanical properties of metal AM components are considerably different than those of traditionally fabricated metal components. Typically, AM components are harder and stronger than cast or wrought parts but tend to show a reduced ductility. Tribological laboratory tests show that some SLM components have more ideal COFs. At high temperatures, the laser metal deposition manufactured samples regularly outperformed traditional steel samples, largely due to the optimized surface patterns, material flexibility, and the ability to produce fully dense claddings with minimal dilution. It should be noted that the microstructure of the metal AM components has been shown to have significant impact on mechanical and tribological properties.

As the interest in AM continues to grow, technologies to enhance the tribological properties are developing alongside. Chemical, mechanical, and laser-based post-processing techniques appear to be a promising avenue to tribological enhancement. As metal AM is optimal to produce complex components, special attention should be given to chemical surface treatments. The strategy of total submersion in chemical baths offers higher surface quality for components with complex geometry. Likewise, laser polishing is a method which holds great potential for further improvement. Passing a laser over each deposited layer before the next is deposited can lead to a significant decrease in surface roughness. These avenues present possibilities, which can be directly included in AM factory lines, thus avoiding the need of cost-intensive post-processing. Further analysis of the resulting microstructure change from laser polishing and its impact on tribological performance is recommended. The traditional methods of polishing, grinding, and tumble finishing have all been proven to reduce surface roughness and improve fatigue strength. As post-processing techniques develop, additively manufactured parts come even closer to becoming ideal alternatives to traditionally manufactured metal components.

The development and strategic use of raw materials has been the focus of several studies, with titanium or aluminum alloys and nickel superalloys all displaying promising tribological and mechanical properties. Nickel superalloys offer the most potential to metal additive manufacturing. When produced via AM, the additively manufactured alloy outperforms cast components. Another promising aspect is microstructure optimization in AM, with potential to adjust the grain morphology to develop better mechanical performance. Further research in this area is needed to determine methods to develop ideal microstructures.

To summarize, metal AM has the potential to replace traditional methods of metal manufacturing. For this to become a reality, further understanding of the mechanical, tribological, and material properties of metal AM must be developed. Surface quality presents an obstacle to the advancement of tribological properties in metal AM. While post-processing is an effective avenue for tribological optimization of metal additively manufactured components, it is a less-than-desirable method, increasing cost and timeframe for fabrication. Consequently, the development of AM materials and microstructure study, conducted with tribological applications in mind, will be the subject of increased interest as sufficient literature is published.

Author Contributions: Conceptualization, methodology, formal analysis, investigation, writing—original draft preparation, and writing—review and editing, R.S., N.P., A.R., K.S. and M.M.; visualization, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: A. Rosenkranz gratefully acknowledges the financial support given by ANID within the project Fondecyt Regular 1220331. M. Marian greatly acknowledges the financial support from the Vicerrectoría Académica (VRA) of the Pontificia Universidad Católica de Chile.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ralls, A.M.; Kumar, P.; Menezes, P.L. Tribological Properties of Additive Manufactured Materials for Energy Applications: A Review. *Processes* **2021**, *9*, 31. [CrossRef]
2. Hashemi, S.M.; Parvizi, S.; Baghbanijavid, H.; Tan, A.T.L.; Nematollahi, M.; Ramazani, A.; Fang, N.X.; Elahinia, M. Computational modelling of process–structure–property–performance relationships in metal additive manufacturing: A review. *Int. Mater. Rev.* **2022**, *67*, 1–46. [CrossRef]

3. Hosseini, E.; Popovich, V.A. A review of mechanical properties of additively manufactured Inconel 718. *Addit. Manuf.* **2019**, *30*, 100877. [CrossRef]
4. Tolosa, I.; Garciandía, F.; Zubiri, F.; Zapirain, F.; Esnaola, A. Study of mechanical properties of AISI 316 stainless steel processed by "selective laser melting", following different manufacturing strategies. *Int. J. Adv. Manuf. Technol.* **2010**, *51*, 639–647. [CrossRef]
5. Guan, K.; Wang, Z.; Gao, M.; Li, X.; Zeng, X. Effects of processing parameters on tensile properties of selective laser melted 304 stainless steel. *Mater. Des. (1980–2015)* **2013**, *50*, 581–586. [CrossRef]
6. Vrancken, B.; Thijs, L.; Kruth, J.-P.; van Humbeeck, J. Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties. *J. Alloys Compd.* **2012**, *541*, 177–185. [CrossRef]
7. Thijs, L.; Verhaeghe, F.; Craeghs, T.; van Humbeeck, J.; Kruth, J.-P. A study of the microstructural evolution during selective laser melting of Ti–6Al–4V. *Acta Mater.* **2010**, *58*, 3303–3312. [CrossRef]
8. Jia, Q.; Gu, D. Selective laser melting additive manufacturing of Inconel 718 superalloy parts: Densification, microstructure and properties. *J. Alloys Compd.* **2014**, *585*, 713–721. [CrossRef]
9. Kanagarajah, P.; Brenne, F.; Niendorf, T.; Maier, H.J. Inconel 939 processed by selective laser melting: Effect of microstructure and temperature on the mechanical properties under static and cyclic loading. *Mater. Sci. Eng. A* **2013**, *588*, 188–195. [CrossRef]
10. Kumar, S.; Pityana, S. Laser-Based Additive Manufacturing of Metals. *AMR* **2011**, *227*, 92–95. [CrossRef]
11. Kumar, S. Selective laser sintering: Recent advances. In *Proceedings of the Pacific International Conference on Applications of Lasers and Optics, PICALO 2010: 4th Pacific International Conference on Laser Materials Processing, Micro, Nano and Ultrafast Fabrication, Wuhan, China, 23–25 March 2010*; Laser Institute of America: Orlando, FL, USA, 2010; p. 607. ISBN 978-0-912035-56-7.
12. Khan, M.; Dickens, P. Selective Laser Melting (SLM) of pure gold. *Gold Bull.* **2010**, *43*, 114–121. [CrossRef]
13. Louvis, E.; Fox, P.; Sutcliffe, C.J. Selective laser melting of aluminium components. *J. Mater. Process. Technol.* **2011**, *211*, 275–284. [CrossRef]
14. Matilainen, V.; Piili, H.; Salminen, A.; Syvänen, T.; Nyrhilä, O. Characterization of Process Efficiency Improvement in Laser Additive Manufacturing. *Phys. Procedia* **2014**, *56*, 317–326. [CrossRef]
15. Qian, M.; Xu, W.; Brandt, M.; Tang, H.P. Additive manufacturing and postprocessing of Ti-6Al-4V for superior mechanical properties. *MRS Bull.* **2016**, *41*, 775–784. [CrossRef]
16. Zhu, J.; Zhou, H.; Wang, C.; Zhou, L.; Yuan, S.; Zhang, W. A review of topology optimization for additive manufacturing: Status and challenges. *Chin. J. Aeronaut.* **2021**, *34*, 91–110. [CrossRef]
17. Bourell, D.L.; Rosen, D.W.; Leu, M.C. The Roadmap for Additive Manufacturing and Its Impact. *3D Print. Addit. Manuf.* **2014**, *1*, 6–9. [CrossRef]
18. Frazier, W.E. Direct Digital Manufacturing of Metallic Components: Vision and Roadmap. In Proceedings of the 21st Annual International Solid Freeform Fabrication Symposium, Austin, TX, USA, 9–11 August 2010. [CrossRef]
19. Campbell, I.; Bourell, D.; Gibson, I. Additive manufacturing: Rapid prototyping comes of age. *Rapid Prototyp. J.* **2012**, *18*, 255–258. [CrossRef]
20. Kruth, J.-P.; Levy, G.; Klocke, F.; Childs, T. Consolidation phenomena in laser and powder-bed based layered manufacturing. *CIRP Ann.-Manuf. Technol.* **2007**, *56*, 730–759. [CrossRef]
21. Cáceres, C.H.; Davidson, C.J.; Griffiths, J.R. The deformation and fracture behaviour of an AlSiMg casting alloy. *Mater. Sci. Eng. A* **1995**, *197*, 171–179. [CrossRef]
22. Atzeni, E.; Salmi, A. Economics of additive manufacturing for end-usable metal parts. *Int. J. Adv. Manuf. Technol.* **2012**, *62*, 1147–1155. [CrossRef]
23. GE Additive. What Is Additive Manufacturing? Available online: https://www.ge.com/additive/additive-manufacturing (accessed on 22 September 2022).
24. Brecher, C. *Integrative Production Technology for High-Wage Countries*; Springer: Berlin/Heidelberg, Germany, 2012; ISBN 978-3-642-21066-2.
25. Brandt, M. (Ed.) *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications*; Elsevier/Woodhead Publishing (Woodhead Publishing is an imprint of Elsevier): Amsterdam, The Netherlands, 2017; ISBN 9780081004340.
26. Zhang, S.; Wei, Q.; Cheng, L.; Li, S.; Shi, Y. Effects of scan line spacing on pore characteristics and mechanical properties of porous Ti6Al4V implants fabricated by selective laser melting. *Mater. Des. (1980–2015)* **2014**, *63*, 185–193. [CrossRef]
27. Khaing, M.; Fuh, J.; Lu, L. Direct metal laser sintering for rapid tooling: Processing and characterisation of EOS parts. *J. Mater. Process. Technol.* **2001**, *113*, 269–272. [CrossRef]
28. Frazier, W.E. Metal Additive Manufacturing: A Review. *J. Mater. Eng. Perform.* **2014**, *23*, 1917–1928. [CrossRef]
29. Shah, R.; Gashi, B.; Hoque, S.; Marian, M.; Rosenkranz, A. Enhancing mechanical and biomedical properties of protheses-Surface and material design. *Surf. Interfaces* **2021**, *27*, 101498. [CrossRef]
30. Ford, S.; Despeisse, M. Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *J. Clean. Prod.* **2016**, *137*, 1573–1587. [CrossRef]
31. Kelly, S.M.; Kampe, S.L. Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part II. Thermal modeling. *Met. Mat. Trans. A* **2004**, *35*, 1869–1879. [CrossRef]
32. Wang, P.; Nai, M.L.S.; Sin, W.J.; Wei, J. Effect of Building Height on Microstructure and Mechanical Properties of Big-Sized Ti-6Al-4V Plate Fabricated by Electron Beam Melting. *MATEC Web Conf.* **2015**, *30*, 2001. [CrossRef]

33. Wang, Z.; Palmer, T.A.; Beese, A.M. Effect of processing parameters on microstructure and tensile properties of austenitic stainless steel 304L made by directed energy deposition additive manufacturing. *Acta Mater.* **2016**, *110*, 226–235. [CrossRef]
34. Meng, Y.; Xu, J.; Jin, Z.; Prakash, B.; Hu, Y. A review of recent advances in tribology. *Friction* **2020**, *8*, 221–300. [CrossRef]
35. Zhu, Y.; Tian, X.; Li, J.; Wang, H. The anisotropy of laser melting deposition additive manufacturing Ti–6.5Al–3.5Mo–1.5Zr–0.3Si titanium alloy. *Mater. Des. (1980–2015)* **2015**, *67*, 538–542. [CrossRef]
36. Dehoff, R.R.; Tallman, C.; Duty, C.E.; Peter, W.H.; Yamamoto, Y.; Chen, W.; Blue, C.A. Case Study: Additive Manufacturing of Aerospace Brackets. *Adv. Mater. Processes* **2013**, *171*, 3.
37. Patel, J.K.; Wilshire, B. The challenge to produce consistent mechanical properties in Nb-HSLA strip steels. *J. Mater. Process. Technol.* **2002**, *120*, 316–321. [CrossRef]
38. Kok, Y.; Tan, X.P.; Wang, P.; Nai, M.; Loh, N.H.; Liu, E.; Tor, S.B. Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review. *Mater. Des.* **2018**, *139*, 565–586. [CrossRef]
39. Ur Rahman, N.; Matthews, D.T.A.; de Rooij, M.; Khorasani, A.M.; Gibson, I.; Cordova, L.; Römer, G. An Overview: Laser-Based Additive Manufacturing for High Temperature Tribology. *Front. Mech. Eng.* **2019**, *5*, 16. [CrossRef]
40. Shah, R.; Woydt, M.; Huq, N.; Rosenkranz, A. Tribology meets sustainability. *Ind Lubr. Tribol.* **2021**, *73*, 430–435. [CrossRef]
41. Special Issue on Tribology of Additive Manufacturing. *J. Tribol. Trans. ASME* **2021**, *143*, 05021. [CrossRef]
42. Rao, B.S.; Rao, T.B. Mechanical and Tribological Properties of 3D printed Al-Si alloys and composites: A Review. *Silicon* **2022**, *14*, 5751–5782. [CrossRef]
43. F42 Committee. *Terminology for Additive Manufacturing Technologies*; ASTM International: West Conshohocken, PA, USA, 2012.
44. Kruth, J.-P.; Mercelis, P.; van Vaerenbergh, J.; Froyen, L.; Rombouts, M. Binding mechanisms in selective laser sintering and selective laser melting. *Rapid Prototyp. J.* **2005**, *11*, 26–36. [CrossRef]
45. Panda, B.K.; Sahoo, S. Thermo-mechanical modeling and validation of stress field during laser powder bed fusion of AlSi10Mg built part. *Results Phys.* **2019**, *12*, 1372–1381. [CrossRef]
46. Asgharzadeh, H.; Simchi, A. Effect of sintering atmosphere and carbon content on the densification and microstructure of laser-sintered M2 high-speed steel powder. *Mater. Sci. Eng. A* **2005**, *403*, 290–298. [CrossRef]
47. Gu, D.D.; Meiners, W.; Wissenbach, K.; Poprawe, R. Laser additive manufacturing of metallic components: Materials, processes and mechanisms. *Int. Mater. Rev.* **2012**, *57*, 133–164. [CrossRef]
48. Robert, P.M.; Nick, W. Laser engineered net shaping advances additive manufacturing and repair. *Weld. J.* **2007**, *86*, 44–48.
49. Xue, L. Laser Consolidation-A One-Step Manufacturing Process for Making Net-Shaped Functional Aerospace Components. In *SAE Technical Paper Series*; Aerospace Manufacturing and Automated Fastening Conference and Exhibition, 11 September 2006; SAE International400 Commonwealth Drive: Warrendale, PA, USA, 2006.
50. Li, Y.; Su, C.; Zhu, J. Comprehensive review of wire arc additive manufacturing: Hardware system, physical process, monitoring, property characterization, application and future prospects. *Results Eng.* **2022**, *13*, 100330. [CrossRef]
51. Bi, X.; Li, R.; Hu, Z.; Gu, J.; Jiao, C. Microstructure and Texture of 2205 Duplex Stainless Steel Additive Parts Fabricated by the Cold Metal Transfer (CMT) Wire and Arc Additive Manufacturing (WAAM). *Metals* **2022**, *12*, 1655. [CrossRef]
52. Zhang, J.; Xiao, G.; Peng, J.; Yu, Y.; Zhou, J. Path Generation Strategy and Wire Arc Additive Manufacturing of Large Aviation Die with Complex Gradient Structure. *Materials* **2022**, *15*, 6115. [CrossRef]
53. Yu, Y.; Qu, Z.; Zhang, J.; Zhou, J. Influence of Surfacing Fe-Based Alloy Layers on Wire Arc Additive Manufactured Ni-Based Superalloys Material on Its Microstructure and Wear Properties. *Materials* **2022**, *15*, 6020. [CrossRef] [PubMed]
54. Sales, A.; Kotousov, A.; Perilli, E.; Yin, L. Improvement of the Fatigue Resistance of Super Duplex Stainless-Steel (SDSS) Components Fabricated by Wire Arc Additive Manufacturing (WAAM). *Metals* **2022**, *12*, 1548. [CrossRef]
55. Pinkerton, A.J. Laser direct metal deposition: Theory and applications in manufacturing and maintenance. In *Advances in Laser Materials Processing*; Elsevier: Amsterdam, The Netherlands, 2010; pp. 461–491. ISBN 9781845694746.
56. Nasiri, M.T.; Movahhedy, M.R. A new design of continuous coaxial nozzle for direct metal deposition process to overcome the gravity effect. *Prog. Addit. Manuf.* **2022**, *7*, 173–186. [CrossRef]
57. Caiazzo, F.; Caggiano, A. Laser Direct Metal Deposition of 2024 Al Alloy: Trace Geometry Prediction via Machine Learning. *Materials* **2018**, *11*, 444. [CrossRef]
58. Samodurova, M.; Logachev, I.; Shaburova, N.; Samoilova, O.; Radionova, L.; Zakirov, R.; Pashkeev, K.; Myasoedov, V.; Trofimov, E. A Study of the Structural Characteristics of Titanium Alloy Products Manufactured Using Additive Technologies by Combining the Selective Laser Melting and Direct Metal Deposition Methods. *Materials* **2019**, *12*, 3269. [CrossRef]
59. Erdakov, I.; Glebov, L.; Pashkeev, K.; Bykov, V.; Bryk, A.; Lezin, V.; Radionova, L. Effect of the Ti6Al4V Alloy Track Trajectories on Mechanical Properties in Direct Metal Deposition. *Machines* **2020**, *8*, 79. [CrossRef]
60. Zhang, D.; Sun, S.; Qiu, D.; Gibson, M.A.; Dargusch, M.S.; Brandt, M.; Qian, M.; Easton, M. Metal Alloys for Fusion-Based Additive Manufacturing. *Adv. Eng. Mater.* **2018**, *20*, 1700952. [CrossRef]
61. Kumar, P.; Chandran, K.S.R. Strength–Ductility Property Maps of Powder Metallurgy (PM) Ti-6Al-4V Alloy: A Critical Review of Processing-Structure-Property Relationships. *Met. Mat. Trans. A* **2017**, *48*, 2301–2319. [CrossRef]
62. Shi, X.; Lu, P.; Ye, X.; Ren, S.; Wang, Y.; Xie, Z.; Ma, Y.; Miao, X.; Wu, M. Study of mechanical and tribological properties of Ti–6Al–4V alloy fabricated by powder bed fusion laser beam. *Powder Metall.* **2022**, 1–13. [CrossRef]
63. Alvi, S.; Neikter, M.; Antti, M.-L.; Akhtar, F. Tribological performance of Ti6Al4V at elevated temperatures fabricated by electron beam powder bed fusion. *Tribol. Int.* **2021**, *153*, 106658. [CrossRef]

64. Todai, M.; Nakano, T.; Liu, T.; Yasuda, H.Y.; Hagihara, K.; Cho, K.; Ueda, M.; Takeyama, M. Effect of building direction on the microstructure and tensile properties of Ti-48Al-2Cr-2Nb alloy additively manufactured by electron beam melting. *Addit. Manuf.* **2017**, *13*, 61–70. [CrossRef]
65. Lu, S.; Tang, H.; Qian, M.; Hong, Q.; Zeng, L.; StJohn, D.H. A yttrium-containing high-temperature titanium alloy additively manufactured by selective electron beam melting. *J. Cent. South Univ.* **2015**, *22*, 2857–2863. [CrossRef]
66. Shen, S.; Wang, H.; He, B.; Zhang, S. Microstructure evolution and phase transformation behavior of Ti17 and γ-TiAl bimetallic structure fabricated by directed energy deposition. *J. Alloys Compd.* **2022**, *907*, 164571. [CrossRef]
67. Khorev, A.I. Complex alloying and microalloying of titanium alloys. *Weld. Int.* **2011**, *25*, 56–63. [CrossRef]
68. Zhu, Z.G.; An, X.H.; Lu, W.J.; Li, Z.M.; Ng, F.L.; Liao, X.Z.; Ramamurty, U.; Nai, S.M.L.; Wei, J. Selective laser melting enabling the hierarchically heterogeneous microstructure and excellent mechanical properties in an interstitial solute strengthened high entropy alloy. *Mater. Res. Lett.* **2019**, *7*, 453–459. [CrossRef]
69. Qiu, Y.; Gibson, M.A.; Fraser, H.L.; Birbilis, N. Corrosion characteristics of high entropy alloys. *Mater. Sci. Technol.* **2015**, *31*, 1235–1243. [CrossRef]
70. Huang, K.J.; Wang, Y.Y.; Lin, X. Microstructure and Wear Resistance of $Cu_{0.9}$NiAlCoCrFe High Entropy Alloy Coating on AZ91D Magnesium Alloys by Laser Cladding. *AMR* **2014**, *989–994*, 246–250. [CrossRef]
71. Prabu, G.; Duraiselvam, M.; Jeyaprakash, N.; Yang, C.-H. Microstructural Evolution and Wear Behavior of AlCoCrCuFeNi High Entropy Alloy on Ti–6Al–4V Through Laser Surface Alloying. *Met. Mater. Int.* **2021**, *27*, 2328–2340. [CrossRef]
72. Rathod, H.J.; Nagaraju, T.; Prashanth, K.G.; Ramamurty, U. Tribological properties of selective laser melted Al 12Si alloy. *Tribol. Int.* **2019**, *137*, 94–101. [CrossRef]
73. Prashanth, K.G.; Debalina, B.; Wang, Z.; Gostin, P.F.; Gebert, A.; Calin, M.; Kühn, U.; Kamaraj, M.; Scudino, S.; Eckert, J. Tribological and corrosion properties of Al–12Si produced by selective laser melting. *J. Mater. Res.* **2014**, *29*, 2044–2054. [CrossRef]
74. Leary, M.; Mazur, M.; Elambasseril, J.; McMillan, M.; Chirent, T.; Sun, Y.; Qian, M.; Easton, M.; Brandt, M. Selective laser melting (SLM) of AlSi12Mg lattice structures. *Mater. Des.* **2016**, *98*, 344–357. [CrossRef]
75. Li, Y.; Shi, Y. Microhardness, wear resistance, and corrosion resistance of AlxCrFeCoNiCu high-entropy alloy coatings on aluminum by laser cladding. *Opt. Laser Technol.* **2021**, *134*, 106632. [CrossRef]
76. Yang, Y.; Lu, J.; Luo, Z.-Y.; Wang, D. Accuracy and density optimization in directly fabricating customized orthodontic production by selective laser melting. *Rapid Prototyp. J.* **2012**, *18*, 482–489. [CrossRef]
77. Carlton, H.D.; Haboub, A.; Gallegos, G.F.; Parkinson, D.Y.; MacDowell, A.A. Damage evolution and failure mechanisms in additively manufactured stainless steel. *Mater. Sci. Eng. A* **2016**, *651*, 406–414. [CrossRef]
78. Yap, C.Y.; Chua, C.K.; Dong, Z.L.; Liu, Z.H.; Zhang, D.Q.; Loh, L.E.; Sing, S.L. Review of selective laser melting: Materials and applications. *Appl. Phys. Rev.* **2015**, *2*, 41101. [CrossRef]
79. Ren, Y.; Liang, L.; Shan, Q.; Cai, A.; Du, J.; Huang, Q.; Liu, S.; Yang, X.; Tian, Y.; Wu, H. Effect of volumetric energy density on microstructure and tribological properties of FeCoNiCuAl high-entropy alloy produced by laser powder bed fusion. *Virtual Phys. Prototyp.* **2020**, *15*, 543–554. [CrossRef]
80. Liu, H.; Sun, S.; Zhang, T.; Zhang, G.; Yang, H.; Hao, J. Effect of Si addition on microstructure and wear behavior of AlCoCrFeNi high-entropy alloy coatings prepared by laser cladding. *Surf. Coat. Technol.* **2021**, *405*, 126522. [CrossRef]
81. Zhao, X.; Chen, J.; Lin, X.; Huang, W. Study on microstructure and mechanical properties of laser rapid forming Inconel 718. *Mater. Sci. Eng. A* **2008**, *478*, 119–124. [CrossRef]
82. Amato, K.N.; Gaytan, S.M.; Murr, L.E.; Martinez, E.; Shindo, P.W.; Hernandez, J.; Collins, S.; Medina, F. Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting. *Acta Mater.* **2012**, *60*, 2229–2239. [CrossRef]
83. Strondl, A.; Palm, M.; Gnauk, J.; Frommeyer, G. Microstructure and mechanical properties of nickel based superalloy IN718 produced by rapid prototyping with electron beam melting (EBM). *Mater. Sci. Technol.* **2011**, *27*, 876–883. [CrossRef]
84. Saunders, M. How Process Parameters Drive Successful Metal AM Part Production, Metal Additive Manufacturing. Available online: https://www.metal-am.com/articles/70927-2/ (accessed on 22 September 2022).
85. Bandyopadhyay, A.; Traxel, K.D. Invited Review Article: Metal-additive manufacturing-Modeling strategies for application-optimized designs. *Addit. Manuf.* **2018**, *22*, 758–774. [CrossRef]
86. Chen, H.; Zhao, Y.F. Process parameters optimization for improving surface quality and manufacturing accuracy of binder jetting additive manufacturing process. *Rapid Prototyp. J.* **2016**, *22*, 527–538. [CrossRef]
87. Dehoff, R.R.; Kirka, M.M.; Sames, W.J.; Bilheux, H.; Tremsin, A.S.; Lowe, L.E.; Babu, S.S. Site specific control of crystallographic grain orientation through electron beam additive manufacturing. *Mater. Sci. Technol.* **2015**, *31*, 931–938. [CrossRef]
88. Facchini, L.; Magalini, E.; Robotti, P.; Molinari, A.; Höges, S.; Wissenbach, K. Ductility of a Ti-6Al-4V alloy produced by selective laser melting of prealloyed powders. *Rapid Prototyp. J.* **2010**, *16*, 450–459. [CrossRef]
89. Zhao, S.; Yuan, K.; Guo, W.; He, Y.; Xu, Y.; Lin, X. A comparative study of laser metal deposited and forged Ti-6Al-4V alloy: Uniaxial mechanical response and vibration fatigue properties. *Int. J. Fatigue* **2020**, *136*, 105629. [CrossRef]
90. Gratton, A. Comparison of Mechanical, Metallurgical Properties of 17-4PH Stainless Steel between Direct Metal Laser Sintering (DMLS) and Traditional Manufacturing Methods. In Proceedings of the National Conference of Undergraduate Research 2012, Ogden, UT, USA, 29–31 March 2012.
91. Shellabear, M.; Nyrhila, O. Advances in Materials and Properties of Direct Metal Laser-Sintered Parts. Available online: https://rm-platform.com/downloads2/send/5-papers/255-paper-lane-2007-eos-shellabear (accessed on 24 September 2022).

92. Jawade, S.A.; Joshi, R.; Desai, S.B. Comparative study of mechanical properties of additively manufactured aluminum alloy. *Mater. Today Proc.* **2021**, *46*, 9270–9274. [CrossRef]
93. Laleh, M.; Hughes, A.E.; Yang, S.; Li, J.; Xu, W.; Gibson, I.; Tan, M.Y. Two and three-dimensional characterisation of localised corrosion affected by lack-of-fusion pores in 316L stainless steel produced by selective laser melting. *Corros. Sci.* **2020**, *165*, 108394. [CrossRef]
94. Du Plessis, A.; Yadroitsava, I.; Yadroitsev, I. Effects of defects on mechanical properties in metal additive manufacturing: A review focusing on X-ray tomography insights. *Mater. Des.* **2020**, *187*, 108385. [CrossRef]
95. Mandal, A.; Tiwari, J.K.; AlMangour, B.; Sathish, N.; Kumar, S.; Kamaraj, M.; Ashiq, M.; Srivastava, A.K. Tribological behavior of graphene-reinforced 316L stainless-steel composite prepared via selective laser melting. *Tribol. Int.* **2020**, *151*, 106525. [CrossRef]
96. Upadhyay, R.K.; Kumar, A. Scratch and wear resistance of additive manufactured 316L stainless steel sample fabricated by laser powder bed fusion technique. *Wear* **2020**, *458–459*, 203437. [CrossRef]
97. Eliasu, A.; Duntu, S.H.; Hukpati, K.S.; Amegadzie, M.Y.; Agyapong, J.; Tetteh, F.; Czekanski, A.; Boakye-Yiadom, S. Effect of individual printing parameters on residual stress and tribological behaviour of 316L stainless steel fabricated with laser powder bed fusion (L-PBF). *Int. J. Adv. Manuf. Technol.* **2022**, *119*, 7041–7061. [CrossRef]
98. Mohd Yusuf, S.; Lim, D.; Chen, Y.; Yang, S.; Gao, N. Tribological behaviour of 316L stainless steel additively manufactured by laser powder bed fusion and processed via high-pressure torsion. *J. Mater. Process. Technol.* **2021**, *290*, 116985. [CrossRef]
99. Yasa, E.; Ay, G.M.; Türkseven, A. Tribological and mechanical behavior of AISI 316L lattice-supported structures produced by laser powder bed fusion. *Int. J. Adv. Manuf. Technol.* **2022**, *118*, 1733–1748. [CrossRef]
100. Li, H.; Ramezani, M.; Li, M.; Ma, C.; Wang, J. Effect of process parameters on tribological performance of 316L stainless steel parts fabricated by selective laser melting. *Manuf. Lett.* **2018**, *16*, 36–39. [CrossRef]
101. Alvi, S.; Saeidi, K.; Akhtar, F. High temperature tribology and wear of selective laser melted (SLM) 316L stainless steel. *Wear* **2020**, *448–449*, 203228. [CrossRef]
102. Bartolomeu, F.; Buciumeanu, M.; Pinto, E.; Alves, N.; Carvalho, O.; Silva, F.S.; Miranda, G. 316L stainless steel mechanical and tribological behavior—A comparison between selective laser melting, hot pressing and conventional casting. *Addit. Manuf.* **2017**, *16*, 81–89. [CrossRef]
103. Li, H.; Ramezani, M.; Li, M.; Ma, C.; Wang, J. Tribological performance of selective laser melted 316L stainless steel. *Tribol. Int.* **2018**, *128*, 121–129. [CrossRef]
104. Zhu, Y.; Zou, J.; Chen, X.; Yang, H. Tribology of selective laser melting processed parts: Stainless steel 316 L under lubricated conditions. *Wear* **2016**, *350–351*, 46–55. [CrossRef]
105. Holovenko, Y.; Antonov, M.; Kollo, L.; Hussainova, I. Friction studies of metal surfaces with various 3D printed patterns tested in dry sliding conditions. *Proc. IMechE* **2018**, *232*, 43–53. [CrossRef]
106. Lester, S.; Longfield, N.; Griffiths, J.; Cocker, J.; Staudenmaier, C.; Broadhead, G. New Systems for Laser Cladding. *LTJ* **2013**, *10*, 41–43. [CrossRef]
107. Torres, H.; Varga, M.; Widder, F.; Cihak-Bayr, U.; Viskovic, O.; Ripoll, M.R. Experimental simulation of high temperature sliding contact of hot rolled steel. *Tribol. Int.* **2016**, *93*, 745–754. [CrossRef]
108. Torres, H.; Varga, M.; Adam, K.; Ripoll, M.R. The role of load on wear mechanisms in high temperature sliding contacts. *Wear* **2016**, *364–365*, 73–83. [CrossRef]
109. Sheng, W.; Liu, D.; Wang, H.M. Microstructure and high-temperature wear behavior of laser clad Ni–Ti–Si ternary metal silicide coatings. *Surf. Coat. Technol.* **2008**, *202*, 2871–2877. [CrossRef]
110. Silva, R.G.N.; Pereira, A.d.S.P.; de Sousa, J.M.S.; Pereira, M.; Silva, R.H.G.e. Tribological comparison of Inconel 625 coatings deposited via laser metal deposition and tungsten inert gas welding process. *J. Laser Appl.* **2020**, *32*, 22034. [CrossRef]
111. Yadroitsev, I.; Smurov, I. Surface Morphology in Selective Laser Melting of Metal Powders. *Phys. Procedia* **2011**, *12*, 264–270. [CrossRef]
112. Maleki, E.; Bagherifard, S.; Bandini, M.; Guagliano, M. Surface post-treatments for metal additive manufacturing: Progress, challenges, and opportunities. *Addit. Manuf.* **2021**, *37*, 101619. [CrossRef]
113. Pyka, G.; Kerckhofs, G.; Papantoniou, I.; Speirs, M.; Schrooten, J.; Wevers, M. Surface Roughness and Morphology Customization of Additive Manufactured Open Porous Ti6Al4V Structures. *Materials* **2013**, *6*, 4737–4757. [CrossRef] [PubMed]
114. Scherillo, F. Chemical surface finishing of AlSi10Mg components made by additive manufacturing. *Manuf. Lett.* **2019**, *19*, 5–9. [CrossRef]
115. Wysocki, B.; Idaszek, J.; Buhagiar, J.; Szlązak, K.; Brynk, T.; Kurzydłowski, K.J.; Święszkowski, W. The influence of chemical polishing of titanium scaffolds on their mechanical strength and in-vitro cell response. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2019**, *95*, 428–439. [CrossRef]
116. Worts, N.; Jones, J.; Squier, J. Surface structure modification of additively manufactured titanium components via femtosecond laser micromachining. *Opt. Commun.* **2019**, *430*, 352–357. [CrossRef]
117. Hackel, L.; Rankin, J.R.; Rubenchik, A.; King, W.E.; Matthews, M. Laser peening: A tool for additive manufacturing post-processing. *Addit. Manuf.* **2018**, *24*, 67–75. [CrossRef]
118. Hofele, M.; Schanz, J.; Roth, A.; Harrison, D.K.; de Silva, A.; Riegel, H. Process parameter dependencies of continuous and pulsed laser modes on surface polishing of additive manufactured aluminium AlSi10Mg parts. *Mat.-Wiss. U. Werkstofftech.* **2021**, *52*, 409–432. [CrossRef]

119. Balachandramurthi, A.R.; Moverare, J.; Dixit, N.; Pederson, R. Influence of defects and as-built surface roughness on fatigue properties of additively manufactured Alloy 718. *Mater. Sci. Eng. A* **2018**, *735*, 463–474. [CrossRef]
120. Edwards, P.; Ramulu, M. Fatigue performance evaluation of selective laser melted Ti–6Al–4V. *Mater. Sci. Eng. A* **2014**, *598*, 327–337. [CrossRef]
121. Spierings, A.B.; Starr, T.L.; Wegener, K. Fatigue performance of additive manufactured metallic parts. *Rapid Prototyp. J.* **2013**, *19*, 88–94. [CrossRef]
122. Bagherifard, S.; Beretta, N.; Monti, S.; Riccio, M.; Bandini, M.; Guagliano, M. On the fatigue strength enhancement of additive manufactured AlSi10Mg parts by mechanical and thermal post-processing. *Mater. Des.* **2018**, *145*, 28–41. [CrossRef]
123. Sagbas, B. Post-Processing Effects on Surface Properties of Direct Metal Laser Sintered AlSi10Mg Parts. *Met. Mater. Int.* **2020**, *26*, 143–153. [CrossRef]
124. Colegrove, P.A.; Martina, F.; Roy, M.J.; Szost, B.A.; Terzi, S.; Williams, S.W.; Withers, P.J.; Jarvis, D. High Pressure Interpass Rolling of Wire + Arc Additively Manufactured Titanium Components. *AMR* **2014**, *996*, 694–700. [CrossRef]
125. Martina, F.; Roy, M.J.; Szost, B.A.; Terzi, S.; Colegrove, P.A.; Williams, S.W.; Withers, P.J.; Meyer, J.; Hofmann, M. Residual stress of as-deposited and rolled wire+arc additive manufacturing Ti–6Al–4V components. *Mater. Sci. Technol.* **2016**, *32*, 1439–1448. [CrossRef]
126. McAndrew, A.R.; Rosales, M.A.; Colegrove, P.A.; Hönnige, J.R.; Ho, A.; Fayolle, R.; Eyitayo, K.; Stan, I.; Sukrongpang, P.; Crochemore, A.; et al. Interpass rolling of Ti-6Al-4V wire + arc additively manufactured features for microstructural refinement. *Addit. Manuf.* **2018**, *21*, 340–349. [CrossRef]
127. Donoghue, J.; Antonysamy, A.A.; Martina, F.; Colegrove, P.A.; Williams, S.W.; Prangnell, P.B. The effectiveness of combining rolling deformation with Wire–Arc Additive Manufacture on β-grain refinement and texture modification in Ti–6Al–4V. *Mater. Charact.* **2016**, *114*, 103–114. [CrossRef]
128. Ye, C.; Zhang, C.; Zhao, J.; Dong, Y. Effects of Post-processing on the Surface Finish, Porosity, Residual Stresses, and Fatigue Performance of Additive Manufactured Metals: A Review. *J. Mater. Eng. Perform.* **2021**, *30*, 6407–6425. [CrossRef]