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ADVANCED MANUFACTURING

Altering the Tribological Properties of Laser Powder Bed Fusion Materials through Various Methods: A Review

Additive Manufacturing has gained prominence in research due to its cost-effectiveness and design flexibility. However, the connection between tribology and Laser Powder Bed Fusion remains inadequately investigated despite its potential. This study examines various direct manufacturing methods (i.e., without post-processing), in order to identify the most effective technique for modifying tribological properties. The wear rate and coefficient of friction are influenced by densification, which is affected by the formation of melt pools and keyholes in the microstructure. Notably, there is conflicting evidence on the most influential processing parameter for wear. Some studies suggest that laser power holds the greatest significance, while others propose that scan angle has a more pronounced effect on wear behaviour. Additionally, texturing emerges as another tribology manipulation method, enabling the entrapment of lubricants and debris within the system. The study also explores the relationship between microhardness, volumetric energy density, wear, and friction.

Keywords:
Additive manufacturing, tribology, volumetric energy density, processing parameters, textured surface.

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INTRODUCTION

Additive Manufacturing (AM) first emerged in the 1980s as a Rapid Prototyping technology [1] and has since been adopted as a manufacturing process in multiple industries, such as: medical, automotive, chemical, and aerospace [2]. AM fabricates parts using a layer-by-layer principle which allows far greater geometrical freedom in designs, therefore enabling highly complex products to be created, and has the potential to reduce design-to-manufacturing time through a single step process [3]. Metallic AM processes, such as Laser Powder Bed fusion (LPBF) and Electron Beam Melting (EBM), also allow the material properties to be tailored during manufacture.

One area where AM has the potential for significant improvement is applications where the wear characteristics of the material are critical. To date, however, there has been limited research between the relationship of Additive Manufacturing processing and the tribological properties of the materials and components produced. In this paper LPBF, which relies on metal powder and laser melting to build the final desired part, will be the primary focus.

TRIBOLOGICAL PROPERTIES AND THEIR SIGNIFICANCE

Tribological properties or behaviour (for example, coefficient of friction and slip ratio) is used to characterise states occurring in a system due to tribology. Wear, friction and lubrication are the three main elements of tribology with various sub-elements within, e.g., surface engineering [4]. There are many wear mechanisms, however, the predominant wear found in LPBF is abrasive as shown by Gopinath et al. [5]. AM has increased in usage in various industries where tribology must be manipulated in order to achieve the desired result and lifetime cycle.

There are several methods of manipulating the tribological properties of SLM materials for instance application of surface coatings, processing parameters, nanomaterials and textured surfaces. Material properties and the microstructure can easily be manipulated using altering processing parameters such as: hatch spacing; scan speed; laser power; scan angle; point distance; and exposure time [6], consequently varying the tribological behaviour of the part. Numerous research is currently being carried out inspecting the relationship between tribology and specifically density and microhardness, however, these properties are usually measured as a consequence of the materials and manufacturing conditions used, rather than designed as an output of the process. For example, Han et al. [7] purposefully manipulated scanning speed and hatch spacing predominately, after thermal behaviour simulations, and produced specimens that had a 39% increase in microhardness in comparison with as-fabricated composite samples. It is thought that the SLM produced components plastically deformed and resulted in grain elongation and deformation .

PROCESSING PARAMETERS AND TRIBOLOGY

The influence of Volumetric Energy Density

The relationship between tribological performance and processing parameters is not extremely clear in previous research. One possible issue is the adoption of the design parameter volumetric energy density ($VED,\ J/mm^3$) for comparison of results, which is calculated as follows:

$$ED_v = \frac{P}{v\,h\,t} \tag{1}$$

where P is laser power, v is the laser scanning speed, h is the hatch spacing between adjacent laser scanning tracks, and t is the layer thickness [8]. VED has restricted the potential of application because it does not have the ability to capture the complex physics of the melt pool, for example Marangoni flow and recoil pressure. Some studies will use different combinations of parameters, for instance using the laser beam diameter instead of hatch spacing [9]. Thomas et al. utilised a normalised ED which considers both processing parameters and material properties:

$$ED^* = \left(\frac{AP}{2\,v\,t\,r}\right) * \left(\frac{1}{0.67\,\rho\,C_p(T_m - T_0)}\right) * \left(\frac{1}{h^*}\right) \tag{2}$$

where A is the material's absorptivity, r is the laser beam radius, ρ is the material's density, is the specific heat capacity, T_m is the melting point, T_0 is the initial temperature of the powder-bed, and h^* is the dimensionless hatch spacing derived from (h/r) [10]. It is immediately clear from the equation that the normalised ED takes into consideration more influential parameters on the specimen. Nonetheless, a limitation of the formula is the absence of absorptivity data for powder materials. Published absorptivity values are often produced using polished metal plates, and therefore have limited relevance to metallic powders. Furthermore, the absorptivity of materials is altered based on the processing parameters used in LPBF thus, published values can be immensely unreliable [11].

Other experimentational work was done by King et al. [12] where a normalised melt pool depth as a function of normalised enthalpy was embedded, to consider the melt pool behaviour as well . Still, beyond the threshold, the normalised enthalpy does not include any other physics that are present in keyhole formation and can pose possible problems. Most formulas utilised in previous research do not explore scan or hatch patterns, the gas flow rate used in the gas chamber, the number of times a layer has been scanned, and various other components [3]. The energy density formula is useful for comparisons but if there are not greatly varying process parameters utilised (limiting different melt pool behaviour), it could lead to incorrect assumptions. Contradictory to most studies, Greco et al. [13] manipulated the volumetric energy density by adopting a constant VED value in experimentation even with varying laser power, layer thickness, and hatch spacing through altering the scanning speed accordingly. Consistent relative densities of up to 99.9% were achieved, further depicting that the VED does not portray the true phenomenon occurring during LPBF printing .

Current research of core processing parameters

Presently, there is a lot of contradictory research in the connection between the tribological behaviour of specimens and processing parameters applied. Li et al. [14] concluded that 316L stainless steel samples produced via SLM with differing laser powers and build-up directions do not considerably influence the coefficient of friction or the wear rate. It was noticeable that lower laser powers produced specimens with more pores and a lower hardness.

Theoretically, a higher wear rate should be expected yet, the results attained demonstrated that these samples, produced at lower laser powers, do not differ immensely from the other samples in their tribological properties, possibly due to plastic deformation eliminating the pores . Contradictory to Li et al.'s research, Sagbas et al. [15] demonstrated that laser power alongside scan speed, scan angle and hatch distance all manipulate the wear behaviour of specimens of Ti6Al4V. Scan angle was responsible for approximately 50% of the contribution ratio, with the other processing parameters having equal contribution. The coefficient of friction and hardness were noticeably affected by the processing parameters, thus the wear resistance of the SLM manufactured parts varied. Pant et al. [16] identified that laser power influences microhardness more in comparison to the core processing parameters. According to Taguchi design the laser power followed by hatch spacing and scan speed influence the specific wear rate the most, juxtaposing both Li et al. and Sagbas et al.

The effect of porous structures on tribology

There is current debate as to whether a controlled porous structure is more beneficiary to wear and friction over a fully dense part. Zhu et al. [17] stated that if material densification is increased (decreasing pores) the tribological performance of 316L stainless steel SLM samples should increase due to more refined grains in the microstructure. Another study by Li et al. [18] showed that, after dry sliding wear tests under different loads, the wear track morphology of the same material produced similar flats and high peak areas with no pores. During testing, the debris formed was forced into the pores due to a high contact pressure, possibly assisting the tribological behaviour of the component along its cycle. Li et al. [19] also witnessed the potential of pores in medical Ti6Al4V printed specimens. The porosity was amended to achieve a structure like that of bone for an orthopaedic application. Samples were printed using a laser power of 180-200W with wear being analysed throughout; it was found that finer and more ordered pores on the surface of the components produced a more desirable friction and wear result. This was a result of extra lubrication being captured in the pores allowing for a better resistance to wear.

Many studies prove that a higher density produces a less porous microstructure, thus a lower coefficient of friction and wear rate. A study by Rathod et al. [20] investigates the effect of SLM specimens built with a single melt (SM) and checkerboard (CB) scanning strategies on density and wear rate. SM samples produced a relative density of 96% while CB specimens were able to achieve a higher relative density of 98.5%. It was shown that the porosity significantly altered the wear rate, and SM samples exhibited a higher wear rate due to an increased number of pores present, therefore, a more predominant abrasive wear mechanism. Pekok et al. [21] depicts an inversely proportional relationship between VED and microhardness. Hence, at lower VEDs an increase in microhardness can be witnessed because of a decrease in melt pool size and temperature gradients allowing for an increase in cooling rate, to create a fine-grained microstructure and restricting dislocation movement. This is despite cracks being visible in the AA2024 SLM fabricated parts as a result of incomplete fusion and porosity. The main obstacle for these parts were small gas pores in the microstructure. On the other hand, fusion holes, unmelted power, alongside hot cracks and irregularly shaped pores were the primary concern for samples outside of the red line . AlMangour et al. [22] demonstrated similar results with better mechanical and tribological properties found at higher densification with reduced scanning speed, since improved binding between the molten particles can be seen.

Printed textured surfaces and their tribological behaviour

Printed textured surfaces has the potential of altering the tribological behaviour of components, by creating pockets for lubrication and wear debris. Currently, there has been limited research in the relationship of printed textured surfaces and SLM specifically. Nonetheless, a study by Wang et al. [23] examines the potential of disc (DTS) and ring (RTS) textured surfaces on the coefficient of friction of 304 stainless steel. It was found that DTS provides a relatively low friction coefficient compared to that of RTS, aiding in the reduction of friction on the system (a pin-on-disk tribometer was adopted). Fielden-Stewart et al. [24] also altered the surface of specimens by modifying the printing angle (45°-90°); it was concluded that the printing angle and surface roughness increased in correlation to one another, the interfacial fracture toughness for adhesive wear also increased accordingly. Another study conducted by Gogolewski et al. [25], similar to that of Fielden-Stewart et al., investigated the formation of convex and concave hemisphere surface textures produced alongside an altering printing angle (0°- 90°). Printing irregularities were visible, such as flattened tops in convex bumps, occasional extra material between the texturing, and irregular powder particles found in the lower areas of the concave hemispheres. A correlation between printing angle, textured surface and surface roughness was not realised, due to an inaccurate metrological control and a varying distribution of the coefficient of friction for each specimen. However, it should be noted that the tribological behaviour was successfully altered using concave and convex hemisphere texturing. The addition of textured surface has the potential to largely manipulate the tribological properties of a component, especially with optimised processing parameter.

FUTURE RESEARCH WORK

Modifying processing parameters with both densification and the addition of pores both have the potential to significantly alter the tribology of a system. Alongside the addition of textured surfaces (for instance triangular and square structures) for an already optimised part could provide the perfect balance of tribological properties.

Conflicts of interest

The author declares no Conflicts of interest.

REFERENCES

[1] T. Wohlers, and T. Gornet, 'History of additive manufacturing' in *Wohlers report 2014: 3D printing and additive manufacturing state of the industry annual worlwide progress report',* Fort Collins (Colorado): Wohlers Associates, p.118, 2014.

[2] M. Averyanova, E. Cicala, Ph. Bertrand, and D. Grevey, 'Experimental design approach to optimize selective laser melting of martensitic 17-4 PH powder: part I – single laser tracks and first layer', *Rapid Prototyping Journal*, vol. 18, no. 1, pp. 28–37, Jan. 2012. doi.org/10.1108/13552541211193476

[3] N. T. Aboulkhair, M. Simonelli, L. Parry, I. Ashcroft, C. Tuck, and R. Hague, '3D printing of Aluminium alloys: Additive Manufacturing of Aluminium alloys using selective laser melting', *Progress in Materials Science*, vol. 106, p. 100578, Dec. 2019. doi.org/10.1016/j.pmatsci.2019.100578

[4] Y. Meng, J. Xu, Z. Jin, B. Prakash, and Y. Hu, 'A review of recent advances in tribology', *Friction*, vol. 8, no. 2, pp. 221–300, Apr. 2020. doi.org/10.1007/s40544-020-0367-2

[5] V. M. Gopinath and S. Arulvel, 'A review on the steels, alloys/high entropy alloys, composites and coatings used in high temperature wear applications', *Materials Today: Proceedings*, vol. 43, pp. 817–823, 2021. doi.org/10.1016/j.matpr.2020.06.495

[6] J. Delgado, J. Ciurana, and C. A. Rodríguez, 'Influence of process parameters on part quality and mechanical properties for DMLS and SLM with iron-based materials', *International Journal of Advanced Manufacturing Technology*, vol. 60, no. 5, pp. 601–610, May 2012. doi.org/10.1007/s00170-011-3643-5

[7] Q. Han, R. Setchi, F. Lacan, D. Gu, and S. L. Evans, 'Selective laser melting of advanced Al-Al 2 O 3 nanocomposites: Simulation, microstructure and mechanical properties', *Materials Science and Engineering: A*, vol. 698, pp. 162–173, Jun. 2017. doi.org/10.1016/j.msea.2017.05.061

[8] Q. Han, R. Setchi, F. Lacan, D. Gu, and S. L. Evans, 'Selective laser melting of advanced Al-Al2O3 nanocomposites: Simulation, microstructure and mechanical properties', *Materials Science and Engineering: A*, vol. 698, pp. 162–173, Jun. 2017. doi.org/10.1016/j.addma.2019.04.018

[9] U. Scipioni Bertoli, A. J. Wolfer, M. J. Matthews, J.-P. R. Delplanque, and J. M. Schoenung, 'On the limitations of Volumetric Energy Density as a design parameter for Selective Laser Melting', *Materials & Design*, vol. 113, pp. 331–340, Jan. 2017. doi.org/10.1016/j.matdes.2016.10.037

[10] M. Thomas, G. J. Baxter, and I. Todd, 'Normalised model-based processing diagrams for additive layer manufacture of engineering alloys', *Acta Materialia*, vol. 108, pp. 26–35, Apr. 2016. doi.org/10.1016/j.actamat.2016.02.025

[11] H. Li, M. Ramezani, M. Li, C. Ma, and J. Wang, 'Effect of process parameters on tribological performance of 316L stainless steel parts fabricated by selective laser melting', *Manufacturing Letters*, vol. 16, pp. 36–39, Apr. 2018. doi.org/10.1016/j.mfglet.2018.04.003

[12] W. E. King e*t al.*, 'Observation of keyhole-mode laser melting in laser powder-bed fusion additive manufacturing', *Journal of Materials Processing Technology*, vol. 214, no. 12, pp. 2915–2925, Dec. 2014. doi.org/10.1016/j.jmatprotec.2014.06.005

[13] S. Greco, K. Gutzeit, H. Hotz, B. Kirsch, and J. C. Aurich, 'Selective laser melting (SLM) of AISI 316L—impact of laser power, layer thickness, and hatch spacing on roughness, density, and microhardness at constant input energy density', *The International Journal of Advanced Manufacturing Technology*, vol. 108, no. 5-6, pp. 1551-1562, May 2020. doi.org/10.1007/s00170-020-05510-8

[14] H. Li, M. Ramezani, M. Li, C. Ma, and J. Wang, 'Effect of process parameters on tribological performance of 316L stainless steel parts fabricated by selective laser melting', *Manufacturing Letters*, vol. 16, pp. 36–39, Apr. 2018. doi.org/10.1016/j.mfglet.2018.04.003

[15] B. Sagbas, G. Gencelli, and A. Sever, 'Effect of Process Parameters on Tribological Properties of Ti6Al4V Surfaces Manufactured by Selective Laser Melting', *Journal of Materials Engineering and Performance*, vol. 30, no. 7, pp. 4966–4973, Jul. 2021. doi.org/10.1007/s11665-021-05573-y

[16] M. Pant, L. Nagdeve, G. Moona, H. Kumar, and A. Sharma, 'Tribological behavior investigation of 316L stainless steel samples processed by selective laser melting', *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 237, no. 4, pp. 718–731, Apr. 2023. doi.org/10.1177/13506501221101797

[17] Y. Zhu, J. Zou, X. Chen, and H. Yang, 'Tribology of selective laser melting processed parts: Stainless steel 316 L under lubricated conditions', *Wear*, vol. 350–351, pp. 46–55, Mar. 2016. doi.org/10.1016/j.wear.2016.01.004

[18] H. Li, M. Ramezani, M. Li, C. Ma, and J. Wang, 'Tribological performance of selective laser melted 316L stainless steel', *Tribology International*, vol. 128, pp. 121–129, Dec. 2018. doi.org/10.1016/j.triboint.2018.07.021

[19] P. Lu, M. Wu, X. Liu, W. Duan, and J. Han, ‘Study on Corrosion Resistance and Bio-Tribological Behavior of Porous Structure Based on the SLM Manufactured Medical Ti6Al4V’, *Metals and Materials International*, vol. 26, no. 8, pp. 1182–1191, Aug. 2020. doi.org/10.1007/s12540-019-00506-w

[20] H. J. Rathod, T. Nagaraju, K. G. Prashanth, and U. Ramamurty, ‘Tribological properties of selective laser melted Al 12Si alloy’, *Tribology International*, vol. 137, pp. 94–101, Sep. 2019. doi.org/10.1016/j.triboint.2019.04.038

[21] M. A. Pekok, R. Setchi, M. Ryan, Q. Han, and D. Gu, ‘Effect of process parameters on the microstructure and mechanical properties of AA2024 fabricated using selective laser melting’, *International Journal of Advanced Manufacturing Technology*, vol. 112, no. 1–2, pp. 175–192, Jan. 2021. doi.org/10.1007/s00170-020-06346-y

[22] B. AlMangour, D. Grzesiak, J. Cheng, and Y. Ertas, ‘Thermal behavior of the molten pool, microstructural evolution, and tribological performance during selective laser melting of TiC/316L stainless steel nanocomposites: Experimental and simulation methods’, *Journal of Materials Processing Technology*, vol. 257, pp. 288–301, Jul. 2018. doi.org/10.1016/j.jmatprotec.2018.01.028

[23] X. Wang, J. Liu, Y. Wang, and Y. Fu, ‘Fabrication of friction-reducing texture surface by selective laser melting of ink-printed (SLM-IP) copper (Cu) nanoparticles(NPs)’, *Applied Surface Science*, vol. 396, pp. 659–664, Feb. 2017. doi.org/10.1016/j.apsusc.2016.11.003

[24] Z. Fielden-Stewart, T. Coope, D. Bacheva, and B. C. Kim, ‘Effect of the surface morphology of SLM printed aluminium on the interfacial fracture toughness of metal-composite hybrid joints’, *International Journal of Adhesion and Adhesives*, vol. 105, p. 102779, Mar. 2021 doi.org/10.1016/j.ijadhadh.2020.102779

[25] D. Gogolewski, T. Kozior, P. Zmarzły, and T. G. Mathia, ‘Morphology of Models Manufactured by SLM Technology and the Ti6Al4V Titanium Alloy Designed for Medical Applications’, *Materials*, vol. 14, no. 21, p. 6249, Oct. 2021. doi.org/10.3390/ma14216249

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