A COMPREHENSIVE REVIEW OF ADDITIVE MANUFACTURING METHODS IN THE FABRICATION OF SELF-LUBRICATING COMPONENTS

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ABSTRACT

This paper presents a methodological approach to conducting a literature review on additive manufacturing (AM), which is a groundbreaking manufacturing technique that involves the successive layering of materials to create components. The use of AM not only reduces manufacturing waste but also saves time and simplifies assembly processes. The current research focused on exploring the advances of AM in fabricating self-lubricating components. By using specific keywords, relevant data sources were extracted from databases. The literature review highlights the extensive exploration of AM in tribological research, demonstrating its successful application in creating self-lubricating components that have yielded positive results.

OPSOMMING

Hierdie artikel bied 'n metodologiese benadering tot die uitvoer van 'n literatuuroorsig oor laag-op-laag vervaardiging, 'n baanbreker-vervaardigingstegniek waarin materiale in opeenvolgende lae neergelê word om komponente te vervaardig. Die gebruik van laag-op-laag vervaardiging verminder nie alleen vervaardigingsafval nie, maar spaar ook tyd en vereenvoudig samestellingsprosesse. Hierdie navorsing het gefokus op die ondersoek van vooruitgang in laag-op-laag vervaardiging in die maak van selfsmerende komponente. Deur spesifieke sleutelwoorde te gebruik, is relevante databronne verkry vanuit databasisse. Hierdie literatuuroorsig beklemtoon die uitgebreide verkenning van laag-op-laag vervaardiging in tribologiese navorsing, en demonstreer die suksesvolle toepassing daarvan in die maak van selfsmerende komponente wat positiewe resultate opgelewer het.

1. INTRODUCTION

The advances in AM techniques are transforming component production across a wide range of industries. These techniques offer tangible benefits in cost savings and operational efficiency [1]. AM has also been explored in the field of tribology, where it is used to fabricate self-lubricating components. Self-lubricating components have gained significant attention in various industrial applications for their low coefficient of friction values and improved wear-resistance performance [2]. These components are used in various applications, from high-temperature turbines to cryogenic environments, aerospace, and biomedical applications. Their adoption is a result of their capacity to slide against a counter-body in the absence of an external lubricant [3]. Self-lubricating components provide better reliability, lower maintenance needs and costs, and a prolonged component life. The reduced need for external lubricants not only cuts down on the operational costs, but also reduces the environmental impact associated with their disposal. In addition, self-lubricating materials help to lower the chances of lubricant contamination in sensitive environments, such as in biomedical devices or food processing equipment [4].

Modern AM techniques, such as electron beam powder bed fusion and directed energy deposition, offer the ability to fabricate complex geometries [5–7] and microstructures with precise control over the material properties [6, 8], in contrast to the traditional manufacturing methods, which also waste resources in the process [9]. Some of these AM techniques also allow the fabrication of parts without the special jigs and fixtures that are required in the traditional subtractive manufacturing processes [10, 11]. This flexibility not only speeds up the production process, but also reduces the initial setup costs and time associated with tooling and fixtures. The ability to produce parts directly from digital models enables rapid prototyping and iterative design, fostering innovation and reducing the time-to-market for new products.

The surface finishing of most printed parts has been identified to be a limiting factor in their direct applicability [12]. However, with the aid of post-printing processes, the desired surface finishes can be attained quicker. So far, no study exists that reviews the status of research on additively manufactured self-lubricating components for the different application conditions, which is a gap our study aimed to fill. In this paper, the authors reviewed the progress made in the field of tribology, a field of science focusing on the study of lubrication, friction, and wear, and the adoption of AM in fabricating self-lubricating components since 2018. This was done by following the systematic literature review (SLR) methodology. The aim was to provide a clear picture of the current research on self-lubricating components that are additively manufactured, and to identify the lubrication mechanisms and AM techniques that had been confirmed and recommended to be fit for implementation through experimental work.

2. RESEARCH METHODOLOGY

The SLR methodology was used in carrying out the work for this review paper. This is a tool for gathering, analysing, and summarising relevant research studies to report the findings [13–15]. In doing so, a SLR summarises the existing literature and helps to identify gaps in the body of knowledge [16]. The approach has six steps: research questions, search strategy design, data extraction results, scrutiny, quality assessment criteria, and data synthesis [17]. The sub-sections that follow describe the steps taken to gain a better understanding of the study following the systematic literature review approach.

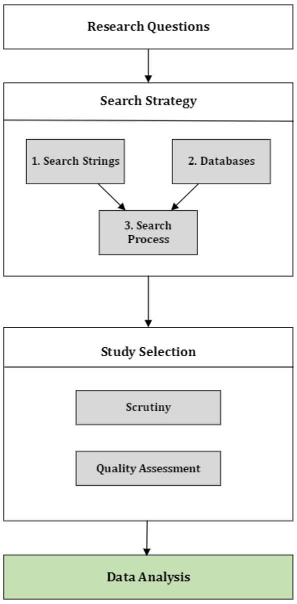

Figure 1: Steps of the systematic literature review protocol

2.1. Research questions

These questions were drafted according to the aim of the study. The main research question of this study was: How successful has the adoption/integration of AM been in the manufacture of self-lubricating components? To address the main question, the following sub-questions needed to be answered:

- RQ1: Has AM been used in the manufacture of self-lubricating components?
- RQ2: How was the lubricant introduced to the system during operation?
- RQ3: For what application are these self-lubricating components being used?
- RQ4: What are the benefits of AM compared with the conventional methods?

2.2. Search strategy design

To answer the identified research questions, a search strategy had to be developed. This step consisted of identifying the key search words and databases, and outlining the actual search process.

2.2.1. Search strings

To identify the key search strings:

- The research questions were analysed to identify the keywords.
- Synonyms and acronyms of the keywords were identified.
- Boolean operators were used to link the key search words in gathering the sources.

Table 1: Identified key search terms

Key search terms
1. Self-lubricating and self-lubrication, keyed in as "self-lubrica*".
2. Additive manufacturing.
3. Additively manufactured.
4. The seven most common additive manufacturing technologies according to ISO/ASTM 52900, keyed in as ("material extrusion" OR "powder bed fusion" OR "material jetting" OR "binder jetting" OR "directed energy deposition" OR "sheet lamination" OR "vat photopolymerisation").
5. The sub-types of the AM processes, keyed in as (DMLS OR EBM OR SLM OR SLS OR FDM).
6. 3d printing and 3d printed, keyed in as "3d print*".

2.2.2. Databases

Scopus and Web of Science databases were used for the primary gathering of the literature sources for this study. The article title, abstract, and keywords were used to search for the published literature sources.

2.2.3. Search process

The keywords were combined using the Boolean operators, and the resulting search terms were keyed into the databases to get the prospective papers.

Table 2: Primary search results

Search terms	Results		Relevant papers	
	Scopus	Web of Science	Scopus	Web of Science
"self-lubrica*" AND ("additively manufactured" OR "additive manufacturing")	35	24	21 (21)	14 (0)
"self-lubrica*" AND "3d print*"	27	8	17 (6)	6 (1)
"self-lubrica*" AND ("material extrusion" OR "powder bed fusion" OR "material jetting" OR "binder jetting" OR "directed energy deposition" OR "sheet lamination" OR "vat photopolymerisation")	10	4	3 (0)	2 (0)
"self-lubrica*" AND (DMLS OR EBM OR SLM OR SLS OR FDM)	22	11	7 (3)	7 (0)

The number in brackets shows the number of relevant publications in the search term that had not already been identified.

2.3. Study selection

This process is illustrated in Figure 2 below. All the results from the primary search were scrutinised to determine whether they were fit for further review. This was done by verifying that the publication documented work that had been carried out on self-lubricating components fabricated through AM. The publication title and abstract were thoroughly examined at this step. One hundred and forty-one literature sources were obtained from the primary study on 19 July, 2023, and after a thorough scrutiny of the title and abstract, only 77 literature sources were discovered to be relevant from both databases. The 77 obtained sources were further compared to check that there were no duplicates, and 47 of these sources were dismissed, leaving 30 for final full-text assessment. The empirical aspects of these 30 sources were then analysed to identify their relevance and whether AM techniques had been used to fabricate self-lubricating components, how lubricity had been achieved, and the exposure conditions for the fabricated components. Upon full-text assessment, it was determined that only 18 of the 30 studies sufficiently addressed the key focus areas of the scoping review within its inclusion criteria.

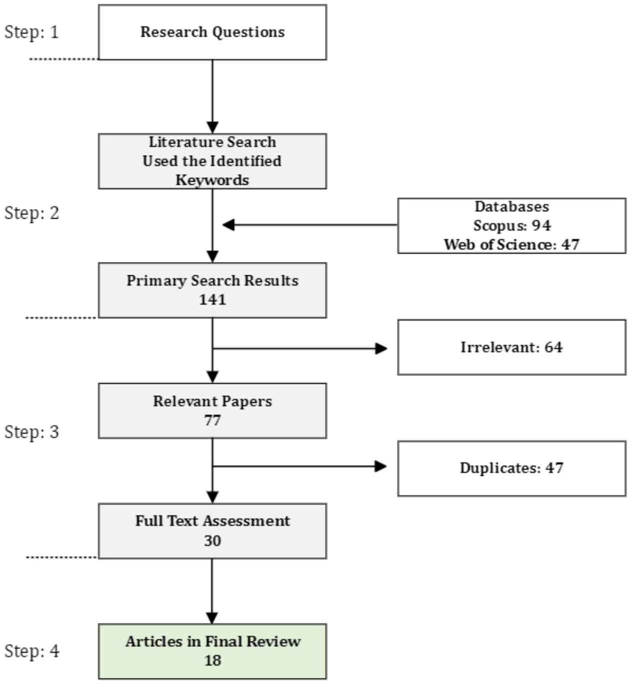

Figure 2: Study selection process

3. EXTRACTION OF DATA

This section focuses on the selected literature sources to identify the highlighted data extraction categories. This will eventually aid in answering the main and sub-research questions. Table 3 below summarises all 18 sources that were selected for the final assessment by highlighting the AM methods they employed, the material used, how lubrication was achieved, and the application conditions.

Table 3: Data extraction

Reference	AM technique used	Material used	How lubricity was achieved	Application
[18]	Direct ink writing	Poly(amide) acid (PAA) containing pore forming agent poly(methyl methacrylate) (PMMA)	Lubricant oils were impregnated into the porous structure	Bearing retainers. In aerospace

Reference	AM technique used	Material used	How lubricity was achieved	Application
[19]	Digital light processing (DLP) 3D printing	polytetrafluoroethylene (PTFE) filled photosensitive polyimide (PSPI)	PTFE micro-powder	Bearings, and sealing rings, which are used in spacecraft, satellites, and automotive products
[20]	Direct laser cladding	$CoCrCu_{1-x}FeNi_x$ High Entropy Alloy (for x = 0, 0.1, 0.3, 0.5)	Oxidation of the HEA coating layer resulted in the formation of self-lubricating CuO	-
[21]	Selective laser melting (SLM)	Ni-based powders mixed with MoS_2 and Al_2O_3 particles	Through the dispersed MoS_2	Coating of cutting tools
[22]	Selective laser melting (SLM)	M50-5wt%Ag-10wt%Ti_3SiC_2 self-lubricating composites	Through Ag and oxides of Ti_3SiC_2	High-temperature applications
[23]	Selective laser melting (SLM)	Inconel 718 (IN718) nickel-based superalloys	Through multi-soft metal (Sn-Pb-Ag) infiltration	Aircraft engine parts – e.g., turbine discs, blades, rotating seals
[24]	Laser metal deposition (LMD)	AlSi10Mg/BNNS composites	Through the dispersed BNNSs	Where there is dynamic load and friction between moving parts
[7]	Selective laser melting (SLM) (for the substrate) and laser metal deposition (LMD) (for the coating)	Maraging steel	Nickel based alloy containing 5 wt% silver and 10 wt% MoS2, and an iron-based alloy containing graphite coatings	Surface protection and functionality in hot forming tools
[25]	Fused deposition molding (FDM)	Polyetheretherketone (PEEK) and NaCl as the porogenic agent	Oil was impregnated into the pores of the base material	Spacecraft bearing units
[26]	Selective laser sintering (SLS) and fused deposition modelling (FDM)	Plastic for FDM; nylon and aluminum-based material for SLS	Micropores were formed within the bearing structure that were then impregnated with commercial engine oil 5w30	Journal bearings
[9]	Laser powder-bed fusion (LPBF)	Ti-6Al-4V (TC4) alloy	PTFE incorporated as the solid lubricant into the honeycomb structure	-

Reference	AM technique used	Material used	How lubricity was achieved	Application
[27]	Laser powder-bed fusion (LPBF)	Ti-6Al-4V (TC4) alloy (Ti-TiN coating)	PTFE incorporated as the solid lubricant into the honeycomb structure	-
[29]	Laser additive manufacturing (LAM)	M50 steel	Graphene	Aircraft bearings
[30]	Laser additive manufacturing (LAM)	M50 steel	Sn-Ag-Cu composites were filled into the microchannels of M50	High-speed and heavy-load applications
[31]	Laser additive manufacturing (LAM)	Ti-6Al-4V (TC4) alloy	Microporous channels filled by Sn-AgCu-Nb2C	-
[32]	Laser additive manufacturing (LAM)	Ti-6Al-4V (TC4) alloy	Ag-multilayer graphene /TC4 alloy self-lubricating composites	-
[33]	Laser melting deposition (LMD)	Ni_3Al-based alloy	Multilayer graphene	-
[34]	Selective laser melting (SLM)	AlSi10Mg composite	Graphene nano-platelets (GNPs)	-

4. ANALYSIS OF RESULTS AND DISCUSSION

This section presents a comprehensive discussion of the key data extraction components related to trends in the publication of research work, the application of AM methods, and the different lubrication mechanisms explored in research.

4.1. Trends in publication of research work

From the studies, the employment of AM methodologies in tribology research is on the rise, as demonstrated in Figure 3 below. Most of the benefits and opportunities that AM offers to tribological research are demonstrated in the research studies that were selected for the final full-text review. The research studies under consideration employed a variety of materials, such as metallic alloys [9, 20–23], metal matrix composites [24, 28, 34], and polymers [18, 19, 25], all of which were able to achieve enhanced properties and performance in the final printed component. This serves as evidence that AM allows for the use of different materials in manufacturing processes.

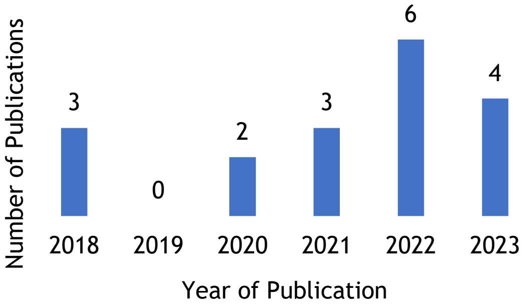

Figure 3: Number of publications per year of publication

AM has also demonstrated its ability to ensure the efficient use of resources and to promote sustainable practices in tribology research by using customised surface textures[9, 27], microstructures, and intricate geometries [30]. These factors have a significant impact on the tribological performance of additively manufactured components. Furthermore, the integration of AM in tribology research encourages interdisciplinary collaboration in research, which encourages the exchange of knowledge and ideas among materials scientists, design engineers, and tribologists. Overall, this enhances the effectiveness and efficiency of the respective fields involved in the research work.

4.2. AM methods explored

The AM techniques are classified into seven common categories according to ISO/ASTM 52900, which can also be further broken down into the sub-categories shown in Figure 4 below. Several factors influence the categorisation of these techniques; these can include the feedstock material used, the mechanisms of delivery of the material, and the energy source, among many others. Most of the studies that explored the fabrication of additively manufactured self-lubricating bearings particularly investigated the subcategories.

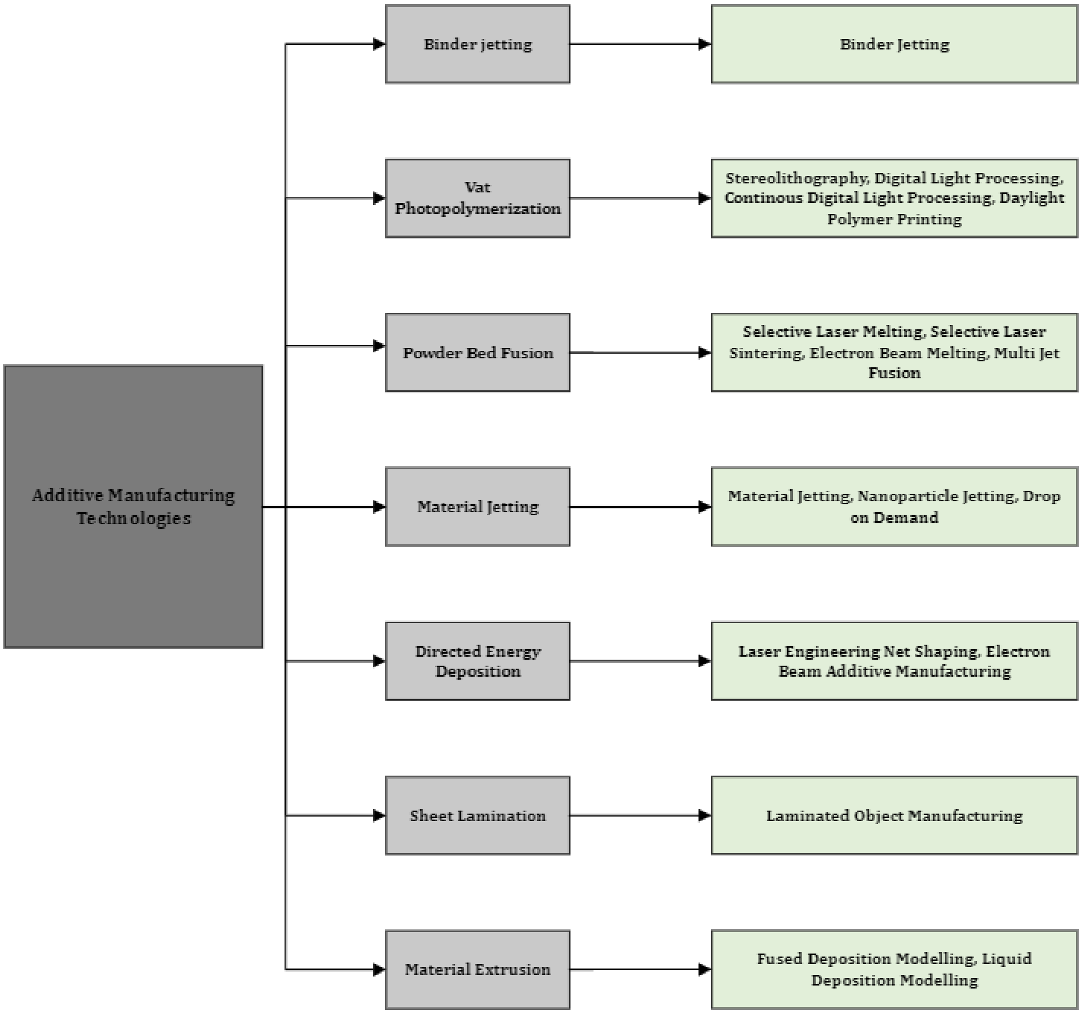

Figure 4: Categories and sub-categories of additive manufacturing technologies

Table 4 below gives short descriptions of each of the seven most common categories.

Table 4: AM techniques and their brief descriptions

AM category	Brief description
Binder jetting (BJ)	BJ selectively projects a binder material within a powder bed containing feedstock material that has been systematically spread to create a single layer of the part [35].
Vat photopolymerisation (VP)	In VPP, the part is fabricated using a liquid photopolymer, with each layer being formed through the rapid solidification of the photopolymer by an ultraviolet laser source. The photopolymer undergoes a chemical reaction upon contact with the laser, which causes it to solidify [35, 36].
Powder bed fusion (PBF)	Thermal energy is used in PBF. An electron beam or a laser can be used as the source of this highly dense energy [36, 37]. Parts are produced through the selective sintering or melting of powder spread on the powder bed. The powder is then incrementally deposited in the building chamber as the bed is lowered [35].
Material jetting (MJ)	MJ components are fabricated through the successive deposition of photopolymer droplets that rapidly solidify upon exposure to an ultraviolet light source [35, 37].
Directed energy deposition (DED)	A focused dense thermal energy is used to fuse materials by melting the feedstock material (metal powder/wire) as it is being deposited [37, 38].
Sheet lamination	This technique involves layering metallic sheets, bonding them together, and then sequentially carving them to create a three-dimensional component [35, 36].
Material extrusion (ME)	ME uses flexible feedstock material that is selectively deposited through a nozzle [38].

The highlighted sub-categories provide distinct capabilities in the fabrication of self-lubricating components. Figure 5 below demonstrates how extensively all the AM categories are being explored in tribology research. The studies were analysed to delve into the main categories and sub-categories of AM techniques and their respective contributions.

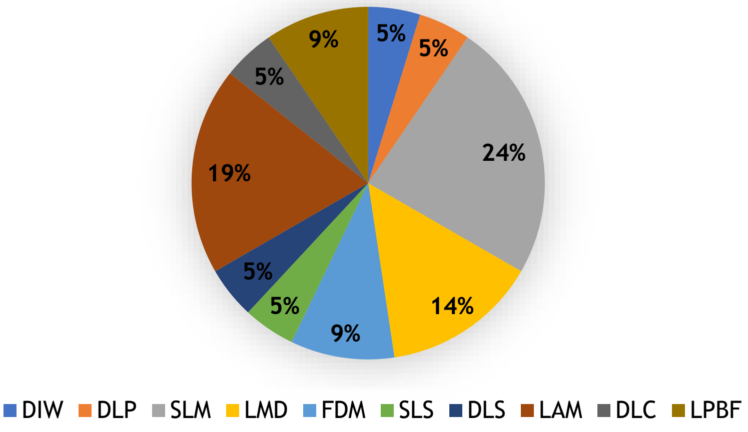

Figure 5: AM methods used in selected studies, and their frequency

Four of the seven main categories of AM techniques have been explored in tribology study. These four processes are material extrusion, vat photopolymerisation, directed energy deposition, and powder bed fusion. Positive results have been reported for all methods, demonstrating enhanced tribological performance [19, 20, 22, 34]. PBF emerged as the most extensively researched AM technique in tribology, accounting for 62% of the total contributions. PBF boasts that it offers short production cycles [39] and has high accuracy and the ability to handle complex geometries, which further enhances its appeal [38]. Another notable advantage is the creation of near-net-shaped components [40], minimising the need for post-processing. The technique's efficient use of materials contributes to its sustainability [41], and the high material utilisation fraction leads to minimal wastage. In addition, powder bed fusion has the capability of yielding fully dense parts [38], resulting in excellent mechanical properties compared with those of its traditionally manufactured counterparts. Within the PBF category, SLM dominates with a combined contribution of 43%. SLS also contributes 10% to the research landscape. However, there is an unassigned contribution of 9%, underscoring the PBF techniques used in tribology research that do not fall neatly into predefined sub-categories.

DED follows PBF with 19% of the contributions, which is made up of 14% LMD and 5% DLC. Just like PBF, DED can also produce fully dense parts [42], and it excels in its ability to add material to an existing surface [43]. This is useful for efficient surface repair and the functional enhancement of components. The efficient surface refurbishment afforded by DED greatly reduces the need for expensive replacements, especially in cases when high-value parts are involved [36]. The surface refurbishment can also leverage the technique's ability to produce relatively large parts [44]. DED's flexibility is further highlighted by its ability to process a wide range of materials, and this enables the creation of parts with customised properties [42].

ME also demonstrated its significant effectiveness in enhancing tribological performance, contributing a significant 14% in total. One of its unique features is its relatively high geometrical accuracy [45], which reduces the post-processing steps. The technique also boasts having a relatively safer feedstock, and it is relatively easier to use.

VP has the smallest contribution, with only 5% of DIW in the overall research landscape. It excels in part accuracy and high forming efficiency [46, 47], ensuring the creation of intricately detailed components while optimising production speed. This technique also delivers impressive part finishes [36]. Its other advantage lies in the option to use different light sources [48], offering the potential to tailor the manufacturing process to specific requirements.

4.3. Lubrication mechanisms

This study also helped to obtain results about the lubrication mechanisms that have been explored in past studies and that are highlighted in Figure 6 below. Solid lubricants, coatings, and impregnation approaches were used to achieve a self-lubricating mechanism. Among these options, solid lubrication emerged as the most extensively researched lubrication mechanism, contributing to 79% of the selected publications' focus. Impregnation was the second most explored method, making up a 16% contribution. Coatings exhibited the least significant contribution, accounting for only 5% of the overall research work.

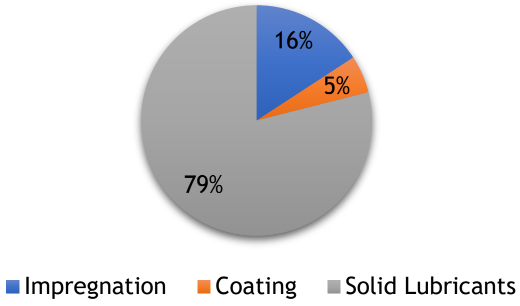

Figure 6: Lubrication mechanisms used in selected studies

The operational efficiency of the equipment depends on the effectiveness and stability of its lubrication. Liquid lubricants and greases are very common lubricating agents owing to their superior lubrication properties, versatility, and ease of use. However, the excessive consumption of these external lubricants poses a significant problem in practice. Effective lubrication, and hence the lubrication mechanism, is crucial for the smooth and reliable operation of various mechanical systems and equipment [4]. It plays a crucial role in minimising friction, reducing wear, and preventing premature failure. The significant reliance of lubricating oils and greases on external lubricant sources presents difficulties, particularly concerning consumption and compatibility in certain specialised contexts. The consumption of these lubricants not only translates into substantial costs, but also has environmental implications owing to resource depletion and waste generation. Furthermore, specific scenarios, such as medical equipment and precision electronics, impose stringent requirements that make the use of liquid lubricants unacceptable. The incorporation of solid lubricants presents a promising solution to diverse lubrication problems. Unlike liquid lubricants, which have limitations in certain applications, different solid lubricants exhibit exceptional efficiency across an extensive temperature spectrum, ranging from -250°C to 400°C [49, 50]. This versatility allows them to function effectively in environments that are characterised by extreme heat or cold. Solid lubricants are desirable in settings with stringent hygienic requirements, such as medical equipment and food processing, where liquid lubricants could compromise cleanliness. In addition, solid lubricants are popular in vacuum conditions, such as those found in precision equipment, where the presence of liquid lubricants could disrupt the precision of the operations [4]. Solid lubricants also offer reduced consumption, resulting in operational cost savings.

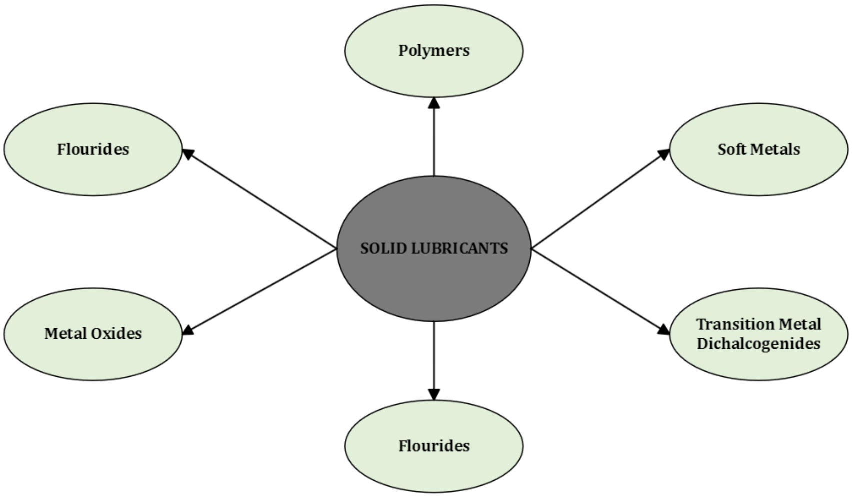

Figure 7: Typical solid lubricants

The self-lubrication process that is facilitated by solid lubricants is a remarkable mechanism that ensures continuous and effective lubrication in a system. This process operates through a series of steps that capitalise on the intentional wear of components, resulting in a reliable and sustained lubrication layer. The initiation of the self-lubrication process is marked by the intentional wear of the relevant component. As the component experiences wear, minute wear particles are generated that are then deposited onto the contact surfaces in the system. These particles adhere to the surface of the rotating component, marking the initiation of the formation of a lubrication layer. This layer develops through a sliding motion that the component undergoes during operation. As the component moves, the adherent wear particles roll along the runway surface, gradually establishing a layer of lubrication. Once this lubrication layer is successfully established on the surfaces, the wear rate of the sliding parts diminishes significantly. This is because the lubrication layer minimises direct contact between the moving surfaces, effectively reducing friction and wear. This process has a continuous self-renewal mechanism: as the part operation progresses, the wear particles in the lubrication layer gradually wear out. Thus new particles need to be generated to replenish the lubricated layer [50].

Coatings lubricate by an intentional wear mechanism such as the principles of solid lubricant incorporation. However, the major difference between the two mechanisms lies in how the lubricant material is incorporated into the base material. In coatings, the lubricant substance is applied only to the contact surface of the substrate, unlike incorporations in which the lubricant is dispersed throughout the material. Therefore, the efficiency of lubrication in coatings relies on the thickness of the applied layer.

Impregnation works on a sweating mechanism where the liquid lubricant is absorbed and stored within the body with a fine networked structure [18, 51]. This guarantees a consistent source of lubrication while ensuring that the lubricant is dispersed sufficiently for effective lubrication. The network may comprise interconnected pores, or could be achieved through uniformly dispersed microscopic particles such as graphene nanotubes. When loaded and subjected to temperature, the retained lubricant is dispensed onto the contacting surfaces, thus making it available for the lubrication process while reducing friction and wear.

5. CONCLUSION AND OUTLOOK

In this paper, a rigorous SLR of self-lubricating components fabricated by AM was conducted. This led to the identification of AM methods and lubrication mechanisms that are being explored for AM adoption in tribology research. The review also highlighted the trends in the fabrication of self-lubricating components using AM processes. The following conclusions can be drawn from this paper:

- There has been an increasing trend in the adoption of AM in tribological research since 2018.
- Four out of the seven AM categories have been successfully investigated in tribological research, and positive results have been attained. These four categories are powder bed fusion, directed energy deposition, material extrusion, and vat photopolymerisation.
- Metal alloys, metal matrix composites, and polymers are the most explored materials in research.
- PBF, particularly SLM, is the most common AM method employed in past studies.
- Solid lubricant incorporation, coatings, and impregnation were identified as the main lubrication mechanisms that had been explored.
- Solid lubricant incorporation was the most explored lubrication mechanism.

For future work purposes, there is a need to explore other AM methods that have not been explored at this point. These are material jetting, binder jetting, and sheet lamination. In addition, it would be important to determine the life cycles that are achievable using AM methods for different exposure conditions. This would help us to understand better the reliability that AM brings about.

DECLARATIONS

Both authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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