Results in Engineering 19 (2023) 101318

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Multi-material additive manufacturing of electronics components: A bibliometric analysis

Thywill Cephas Dzogbewu [a,d,*], Nathaniel Amoah [b], Sampson Afrifa Jnr [c], Samuel Koranteng Fianko [c], Deon Johan de Beer [d]

[a] *Department of Mechanical and Mechatronic Engineering, Faculty of Engineering, Built Environment and Information Technology, Central University of Technology, Bloemfontein, 9301, South Africa*
[b] *Department of Economics and Management, Universita Degli Studi di Brescia, 25121, Brescia, Italy*
[c] *Department of Business Support Studies, Central University of Technology, Bloemfontein 9301, South Africa*
[d] *Centre for Rapid Prototyping and Manufacturing, Central University of Technology, Bloemfontein, South Africa*

ARTICLE INFO

Keywords:
Multi-materials
Additive manufacturing
Interfacial bond
Electronic components
Dissimilar materials
Mechanical interlocking

ABSTRACT

The study presents a bibliometric analysis of studies conducted on multi-materials printing of electronic components via additive manufacturing technologies. Using the R package and the associated biblioshiny, the study analyzed publications from Web of Science and Scopus. The study analyzed 405 research articles after removing 104 duplicates. The study applied performance analysis, keyword analysis, and network analysis. The performance analysis showed that the publications on multi-materials additive manufacturing are multi-disciplinary. Whilst the publications span almost three decades, most contributions started after 2015. The United States of America is the country with the highest production. The keyword analysis showed a changed focus before and after 2015. The trending topics show that the most recent trend is in the 'aerospace industry'. Finally, the thematic analysis shows that the emerging themes in the area are interfaces, moisture, diffusion, microstructure, mechanical properties, and powder metallurgy. These emerging themes are discussed as they are conceived as the future directions of multi-materials printing of electronic components and devices. The current trend of research focuses on understanding and improving the interfacial bonding between the various multi-material interfaces. Overcoming the weak interfacial bonding issues would improve the mechanical properties of multi-materials electronic components.

1. Introduction and motivation

Additive manufacturing (AM) has revolutionized the manufacturing industry and has been considered a pivot for industry 4.0 [1,2]. Several businesses have widely adopted AM in the automotive, aerospace, medical, and electronics industries [3]. It gained its popularity through the use of single material to produce complex three-dimensional (3D) images layer-by-layer [2,4]. As the manufacturing industry is constantly evolving, the current demand is to produce 3D structures with multi-material properties [5], implying manufacturing a single 3D object with different material properties in defined locations. Multiple/Multi-Material Additive Manufacturing (MMAM) technology has led to the production of objects with the desired properties in strategic locations based on the functional requirements of the final products [6,7]. The MMAM process created opportunities for rapid design and direct manufacturing of multifunctional devices and systems monolithically [8], without the use of a complex manufacturing process and expensive tooling [9]. The process fosters innovations and product optimizations since the selected materials are varied within the manufactured products [2].

ISO/ASTM TR 52912 [10] defined the MMAM process as "a layer-by-layer fabrication technique that intentionally modifies process parameters and gradationally varies the spatial of material(s) organization within one component to meet intended function". Girnth et al. [11] defined the MMAM strategy based on the geometrical dimensions in which the material is graded and the number of different materials used. Accordingly, to their definition, a hybrid AM 3D component is produced when only two materials are used, and MMAM 3D component

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* Corresponding author. Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Built Environment and Information Technology, Central University of Technology, Bloemfontein 9301, South Africa.

E-mail address: tdzogbewu@cut.ac.za (T.C. Dzogbewu).

https://doi.org/10.1016/j.rineng.2023.101318
Received 27 May 2022; Received in revised form 20 February 2023; Accepted 16 May 2023
Available online 29 July 2023
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is produced when more than two different materials are used. The authors would like to align the definition of MMAM in this article with ISO/ASTM TR 52912 definition involving more than one material. The Multi-Material Additive Manufacturing (MMAM) technology allowed material components to be varied in a controlled manner, an evolutional paradigm shift from the traditional fabrication methods [12]. The MMAM permitted the manufacturing of near-net products with blended interfaces. Each of the interfaces is developed with different materials depending on the functional requirements of each interface [6,7]. The manufacturing of the 3D products with different interfaces that response differently could be considered analogous to the emerging 4D printing [9]. The 4D printing process has been described as printing a 3D structure with smart materials that respond to external stimuli from the environment, resulting in a change in shape or physical properties over time. Time is added as the fourth dimension (4D) that triggers the change in a 3D-printed object in response to a change in the environment. The litterateur reveals that some studies have focused on the reversibility of 3D printed shape memory materials (4D) that could be used to print electron components with multiple material properties [1,9,13].

MMAM is envisaged to provide desired properties in strategic locations/interfaces permitting localized optimization, such as thermal conductivity in conformal cooling channels; wear resistance, vibration damping, thermal insulation coatings, high hardness, and high-temperature resistance properties in turbines engines; increasing the lifetime and efficiency of tools with abrasive wear environment by combing hot work steel and tungsten carbide/cobalt; dielectric and magnetic properties in antenna and meta-materials; optical properties in laser telecommunication systems; inclusion of embedded components such as resistors, sensors in electrical devices [14,15]. The layer-wise manufacturing strategy employed by the AM process opens the window of possibility of incorporation/embedding various electronic components into 3D build parts during the manufacturing process monolithically as opposed to the multiple assembly steps of the conventional manufacturing methods [16,17].

1.1. *AM process used to manufacture multi-materials*

ISO/ASTM52900-15 [18] classified the AM manufacturing systems into seven categories (material extrusion, vat photopolymerization, powder bed fusion, material jetting, direct energy deposition, sheet lamination, and binder jetting) according to their mechanism of operation. Each of the seven manufacturing systems has unique manufacturing principles, feedstock, advantages, and disadvantages, as summarised in Table 1.

Since each AM system has its unique strength, a new strategy in the manufacturing industry is the combination of the various manufacturing systems to build a component, normally termed hybrid additive manufacturing (HAM). The HAM process can directly produce a 3D electronic device (direct writing of electronic circuitry) with different properties with dissimilar materials (Fig. 1), such as integrated dielectric devices, conductors, semiconductors, magnetic flux sensors, highly stretched LED boards, customized Li-Ion batteries, photodetectors [14,28–31]. The MMAM process is not only able to produce multifunctional electronic devices monolithically but also miniaturize the electronic devices to a smaller footprint [32]. Espalin et al. [28] reported that NASA produced a miniaturized 3D electronic device to develop the next-generation space exploration vehicle, a CubeSat Trailblazer was launched with embedded miniaturized 3D electronic device occupying only 10% of the available 10 × 10 × 10-cm CubeSat enclosure. The MMAM CubeSat was embedded in a modular system as secondary payload to increase accessibility to space. The miniaturized CubeSat MMAM electronic devices have less than 25 consolidated components compared to the original version of 150 components, leading to a 50% reduction in weight and a 20% increase in stiffness, resulting in six times fewer possible failure locations [33]. The 3D printing of the

Table: 1
AM systems used for manufacturing multi-materials.

AM Systems	Type of machine	Printable material	Mechanism of printing	Advantages	Disadvantages	Ref
Powder bed fusion	Selective laser sintering (SLS) Electron beam melting (EBM) Selective laser melting (SLM)	Metallic Ceramics Polymers Composite	Uses electron or laser beam to build 3D objects selectively	High dimensional accuracy Large material database High-value products	High residual thermal stress	[17,19]
Directed energy deposition	Laser Deposition Welding (LDW) Laser-engineered net shaping(LENS)	Metallic Ceramics polymers	Using laser beam to build 3D objects selectively	Large material database Strong interface strength High-value products	Low dimensional accuracy High residual thermal stress	[20,21]
Sheet lamination	Laminated object manufacturing (LOM) Ultrasound additive manufacturing (UAM)	Metals plastic Papers	Sheets of materials are joined one after the other either by adhesive, wielding or thermal bonding	Low cost	Weak interface strength	[20,22]
Material extrusion	Fuse deposition modelling (FDM)	Polymers Food Living cells	Material is drawn through a nozzle, heated and deposited layer by layer	Large material database Low-cost	Poor surface quality Limited printing resolution Weak interface strength	[20,23]
Material jetting	Drop-On-Demand (DOD) PolyJet technology Nano-Particle-Jetting (NPJ)	Polymers Ceramics, Composite Biologicals and hybrid	Printhead dispenses droplets of photosensitive material that solidifies layer-by-layer, under ultraviolet (UV) light	Printing of multiple materials simultaneously High printing resolution	A limited selection of materials Higher material cost Poor mechanical properties degradation of a material due to its photosensitive nature	[20,24]
Binder jetting	Binder jetting (BJ)	Metals Sands Polymers Ceramics Composites	A liquid binding agent is selectively deposited to join powder particles	Large material database	Weak interface strength	[25,26]
Vat photopolymerization	Stereolithography (SLA) Digital light processing (DLP) Carbon® Digital Light Synthesis (DLS)	Polymers	Selectively curing of photo-reactive polymers by using a laser, light or ultraviolet (UV)	High dimensional accuracy	Cross-contamination between materials Limited materials (only photopolymers)	[20,27]

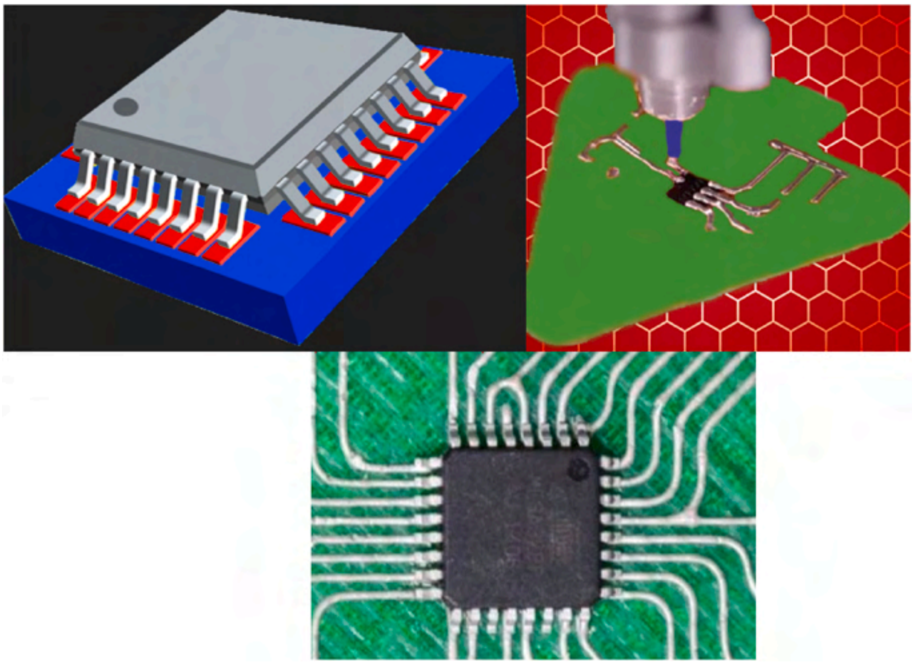


Fig. 1. Schematic representation of fabricated electron device with AM methods.

multi-material enhances the electronic devices' mechanical properties, enabling the device to withstand the harsh condition of space - extreme thermal cycling, low pressure, radiation, etc. The direct writing of the multi-materials is an excellent tool to print electronic devices conformable to any arbitrary shape, as demonstrated by NASA [32].

Valentine et al. [34] produced stretchable strain and pressure sensors using thermoplastic polyurethane as a matrix and thermoplastic polyurethane with silver flakes as a conductive material monolithically. Zhang et al. [35] also printed a highly stretchable electronic LED board with up to 1300% stretchability. The 3D-printed LED has a high-resolution and high fidelity (up to 7 μm) and can maintain electric conductivity even under large deformation. The MMAM process was used by Park et al. [36] to print five different materials; a transparent anode, a photoactive layer, an electrically insulating layer, a cathode, and a silver nanoparticle inter-connecter on a single platform to build a photodetector that achieved an external quantum efficiency of 25.3%. The approach was extended to print integrated multifunctional devices consisting of optically coupled photodetectors and light-emitting diodes circuitry of arbitrary geometries. Wei et al. [29] demonstrated the revolutionary strength of the MMAM methods to produce lithium-ion batteries (LIBs) of thick semisolid electrodes that exhibit high capacity with customized geometries. The HAM manufacturing capability of AM systems holds innovative promise. As the various AM systems attain maturity, manufacturing complex functional electronics systems will continue to emerge. Roach et al. [37] integrate four AM technologies; inkjet (IJ), fused filament fabrication (FFF), direct ink writing (DIW), and aerosol jetting (AJ) onto one single manufacturing platform along with robotic arms for pick-and-place photonic curing for intense pulsed light (IPL) sintering. The HAM was used to produce complex electronic devices, providing a wide range of functionalities with applications ranging from soft robotics and flexible electronics to medical devices. Valentine et al. [34] use the HAM strategy to produce electrical circuitry by directly printing insulating matrix and conductive electrode inks and integrating passive and active electrical components to produce the desired electronic circuitry. The components are then interconnected via printed conductive traces - the fabricated ecteronic devices could be used in wearable electronics, soft robotics, and biomedical devices. It is also documented that Zhang et al. [30] use HMA to fabricate electronics circuitry that requires the printing high viscous conductive materials containing high concentrations of metal particles or carbon-based materials. The authors combined DIW manufacturing systems with MJ and DLP to fabricate fast-response, stiffness-tuneable soft actuators. The actuators demonstrated stiffness up to 120 times without sacrificing flexibility and adaptivity. The hybrid additive manufactured actuators were embedded with a printed Joule-heating circuit and fluidic cooling microchannel circuit that enable the actuators to complete a softening–stiffening cycle within 32 s. Such multiply components manufacturing on a single platform is almost impossible using one AM manufacturing strategy.

Although there are a number of review publications on MMAM and electronic devices [12,38–41], there seems to be no systematic review on MMAM electronic devices. The purpose of this study, therefore, is to examine the trend of MMAM of electronic components, investigate the themes of MMAM of electronic components in publications, recognizing prolific scholars and their contributions to the field of MMAM of electronic components, and exploring publication networks and collaborations across institutions, countries, and regions over time. The study also aims to identify any shifts in the research boundaries related to MMAM of electronic components, based on a substantial body of existing research. The findings of this study will be valuable to researchers, particularly those who are interested in and are new entrants in th field newly. New researchers, for example, can easily locate top articles based on citation counts, prolific authors, and research hotspots. In addition to information such as current themes and thematic future directions, smart learning environments can help researchers make research interest decisions. This study's key research question is: *how has research in the MMAM of electronic components grown through time in terms of scientific output, theme breakthroughs, scholar contributions, and future thematic direction?* A bibliometric analysis is relevant for this study since it attempts to give a comprehensive overview of the MMAM of electronic components.

2. Methodology

2.1. Bibliometric analysis

The methodology applied to this study was bibliometric and thematic analyses of the cluster of research networks. The thematic analysis of the publications over the years was undertaken to provide an understanding of the trends of research and to provide clarity to the groups of studies conducted in the field of MMAM. According to Cooper [42], "Bibliometric methods estimate how much influence or impact a selected research article has on future research. It usually does this by counting the number of times the article is cited after it is published". Applying this to an entire research field helps researchers to examine the trends and impact of the entire research area, as explained by Donthu et al. [43]. The subsequent sections describe the sampling, data collection and other procedures undertaken.

2.2. Sampling

The study focuses on the application of multi-material printing of electronic components. It was also found that several studies used the term functional graded materials instead of multi-materials. It was, therefore, necessary to include the latter in the search. Also, since the study is about the application of multi-materials in the production of electronic devices, the word "electronic" was added to each line of the search words. The Bullion words "OR" and "AND" became useful to streamline the search. All searches were made using topics that included titles, keywords, and abstracts. In unison, the search terms used in both web of Science and Scopus were the same. The following were the search terms used:

> "multi-materials*" AND "electronic*" OR "Functional* graded materials" AND "electronic*" OR "Additive manufact* AND multi-materials*" AND "electronic*" OR "Additive manufact* AND Functional* graded materials" AND "electronic*" OR "3d print* AND multi-materials*" AND "electronic*" OR "3d print* AND Functional* graded materials" AND "electronic*"

The keywords combination means that publications that have multi-materials, electronic, additive manufacturing, and 3d printing in their title, abstracts, keywords, or abstracts or had functional(ly) graded materials and electronic(s) in their title, abstracts, keywords or abstracts would be added to the study.

2.3. Data collection and processing

After inserting these keywords in the search engines, Web of Science produced 245 publications, whilst Scopus produced 264 publications. Due to the exploratory nature of the paper, the search was not restricted (e.g., by language or type of publication). One hundred and four (104) duplicates were found and removed from the data using the R package. The two data sources were combined using the "mergeDbSources" function on R. The final total number of publications included in the final analysis was therefore, 405.

2.4. Analysis tools

A three-phase process was used to discover insights into MMAM research. In the first phase, the study concentrated on two types of bibliometric indicators in this study: (1) traditional bibliographical data such as authors, affiliations, sources (e.g., journal names), and publication year; and (2) terms (e.g., words and phrases) extracted from the titles and abstracts of research articles using natural language processing techniques. This section of the analysis made use of the R package and biblioshiny. At this stage, clusters were also identified, which aided in the selection of articles for evaluation in the second phase of this review. The second phase is the science mapping analysis. This was done to identify the various collaborations between the citations and, finally, the network mapping, which shows the major clusters in the research area.

2.5. Software package and bibliometric analysis

The "***bibliometrix R-package***" software was used. The R package is open-source software that provides a set of tools for undertaking quantitative research in bibliometrics. Aria and Cuccurullo [42] created the R-package, which is written in the R programming language [42]. It contains the most important algorithms for statistical and scientific mapping analysis. The web interface app (***Biblioshiny***) was introduced in recent versions of the bibliometrix R-package (i.e., 2.0 upwards) to assist users without coding abilities in conducting bibliometric analysis. Data can be imported in BibTex, CSV, or Plain Text format from Scopus or Web of Science databases via the Biblioshiny interface. Biblioshiny also allows one to filter data. This study took advantage of the features of biblioshiny for bibliometrix to import the combined WoS and Scopus datasets from the R package.

3. Results and discussions

The results reflect the growth and trends of MMAM research in terms of publication output, distribution, source, citations, prolific scholars, affiliations, social networks, and the field's thematic focus.

3.1. Data synthesis

The literature reveals that AM manufacturing concepts started in 1984, and it was only in the 1990s that its application to multi-materials began [43]. Hence, the current research would consider articles published over the past two decades, beginning in 1996, based on the data extracted from Scopus and web of Science. The synthesized data for the bibliometric analysis is shown in Table 2. It presents a descriptive summary of the studies on MMAM.

3.2. Performance analysis

Performance analysis investigates the contributions of research constituents to a certain topic. The descriptive quality of the analysis is the hallmark of bibliometric investigations [44]. It is very important to

Table 2
Data synthesis and Descriptive.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1996:2022
Sources (Journals, Books, etc)	291
Documents	405
Average years from publication	7.85
Average citations per documents	18.35
Average citations per year per doc	2.517
References	15054
DOCUMENT TYPES	
article	207
article; early access	2
article; proceedings paper	5
book	2
book chapter	4
conference paper	104
conference review	5
proceedings paper	48
review	28
DOCUMENT CONTENTS	
Keywords Plus (ID)	2988
Author's Keywords (DE)	1141
AUTHORS	
Authors	1392
Author Appearances	1734
Authors of single-authored documents	22
Authors of multi-authored documents	1370
AUTHORS COLLABORATION	
Single-authored documents	27
Documents per Author	0.291
Authors per Document	3.44
Co-Authors per Documents	4.28
Collaboration Index	3.62

present the performance of different research constituents (e.g., the nature of the topic under investigation, the research approach, authors, institutions, countries, and journals) in the field.

Fig. 2 demonstrates that the nature of the research approach for MMAM is multi-disciplinary. The various field of study involved in multi-materials research attests to the fact that MMAM research is multi-disciplinary in nature. Multi-disciplinary research derived its strength from using a cooperative and coordinated effort of different experts (shared knowledge) from different disciplines to solve a particular problem [45]. National Academy of Sciences [46] defined multi-disciplinary research as "a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice." MMAM is beyond the scope of a single discipline. A particular disciplined may be required to develop the multi-materials, another disciplined may be required to process the multi-materials, and another discipline may be required to consider its industrial applications (Fig. 3).

Knowledge from different scientific backgrounds is required for a successful realization of MMAM of electronics components for various industrial applications. The multi-disciplinary research approach adopted towards the MMAM process and applications would minimize the partial or one-sided result, resulting in synergy between several disciplines to achieve the necessary recourse of other disciplines.

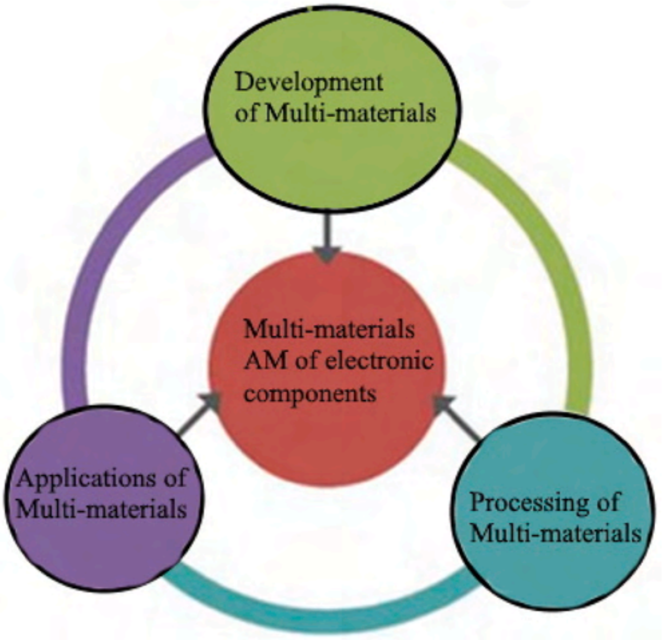


Fig. 3. Interdisciplinary nature of MMAM of electronic components.

3.3. *Trends in the annual number of publications and projection*

Fig. 4 shows the distribution of articles in terms of publication year for papers produced and developed over the period of twenty-six (26) years [1996–2022]. The total publishing trend of MMAM of electronic devices-related articles shows that 2020 was the most productive year, with forty-three (43) articles published, closely followed by forty-two (42) articles in 2021. There was a decline in 2019. A steeper slope of the graph could be observed from 2015, suggesting that higher than the previous annual average publications were published after 2015. In general, there has been a rise in the number of publications of MMAM. The past eight years [starting from 2015] have witnessed a huge interest in the topic of MMAM, with the past six years specifically recording an unprecedented number of publications in MMAM. The graph (Fig. 4) shows that consistency in publication growth began in 2015. The annual growth rate of the MMAM publications (before 2015) was quite low (an annual growth rate of 9.43%). However, the annual growth rate from 2015 to 2022 is 50.38%.

The annual growth of articles was projected to 2030 at 95% confidence. The results show an expected increase in the articles published in MMAM from forty-two (42) articles in 2021 to fifty-five (55) in 2030. Interest in the area is therefore expected to increase over the next years. This is in accordance with the current industrial requirements of MMAM [16,47]. The AM systems have been used successfully to fabricate many complex products with only one material property [48]. The current

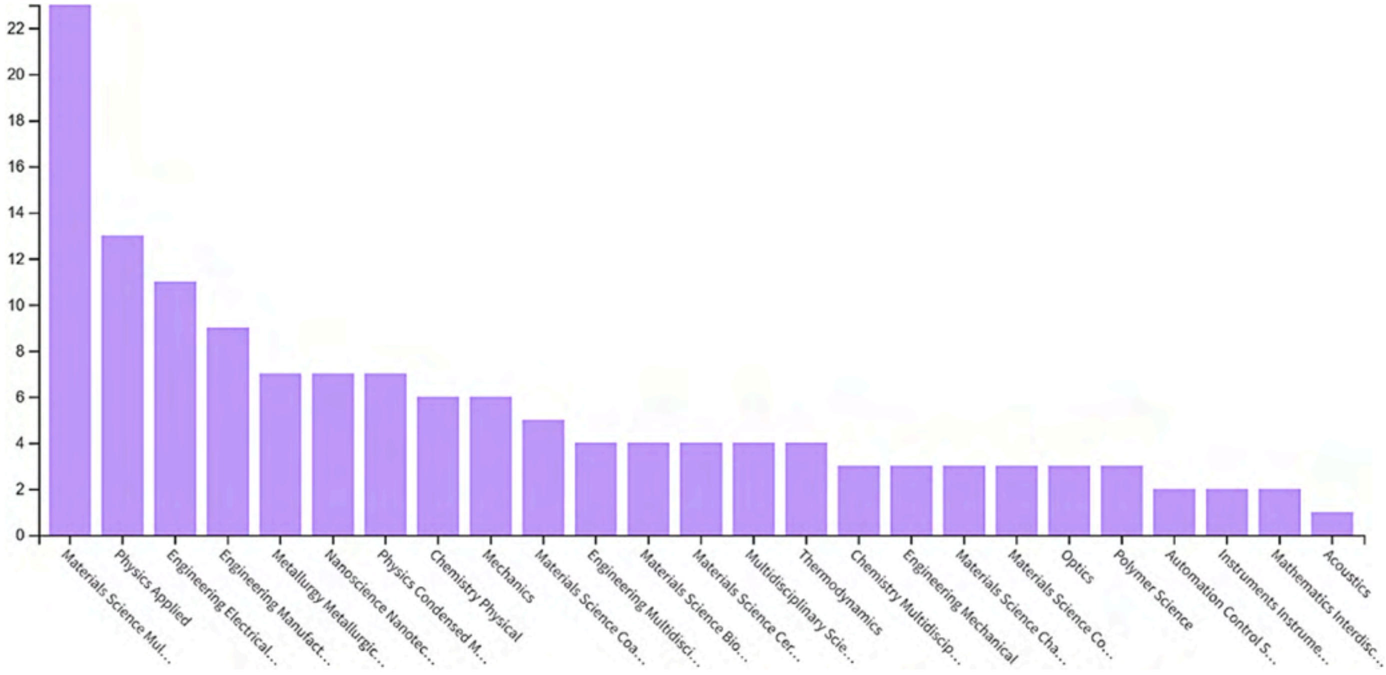


Fig. 2. Performance analysis.

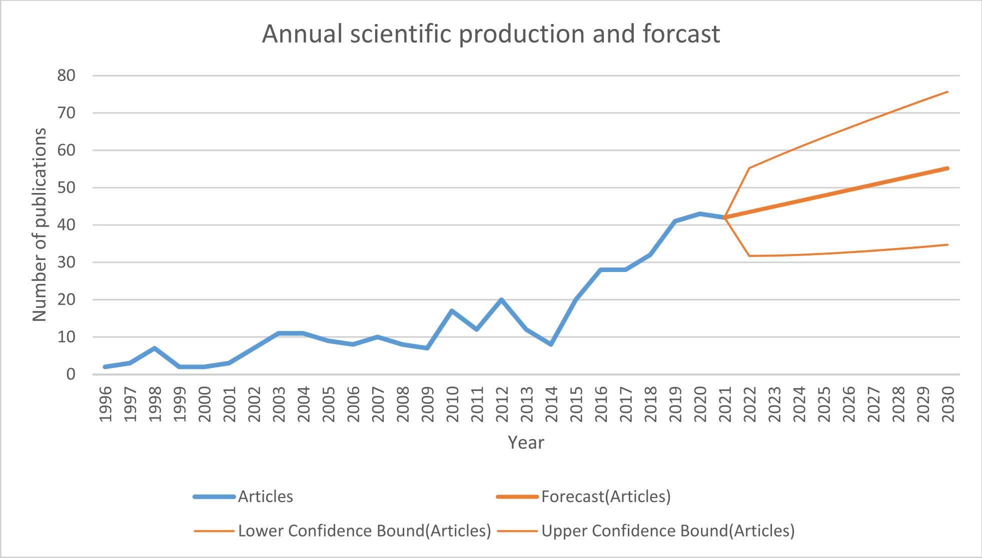
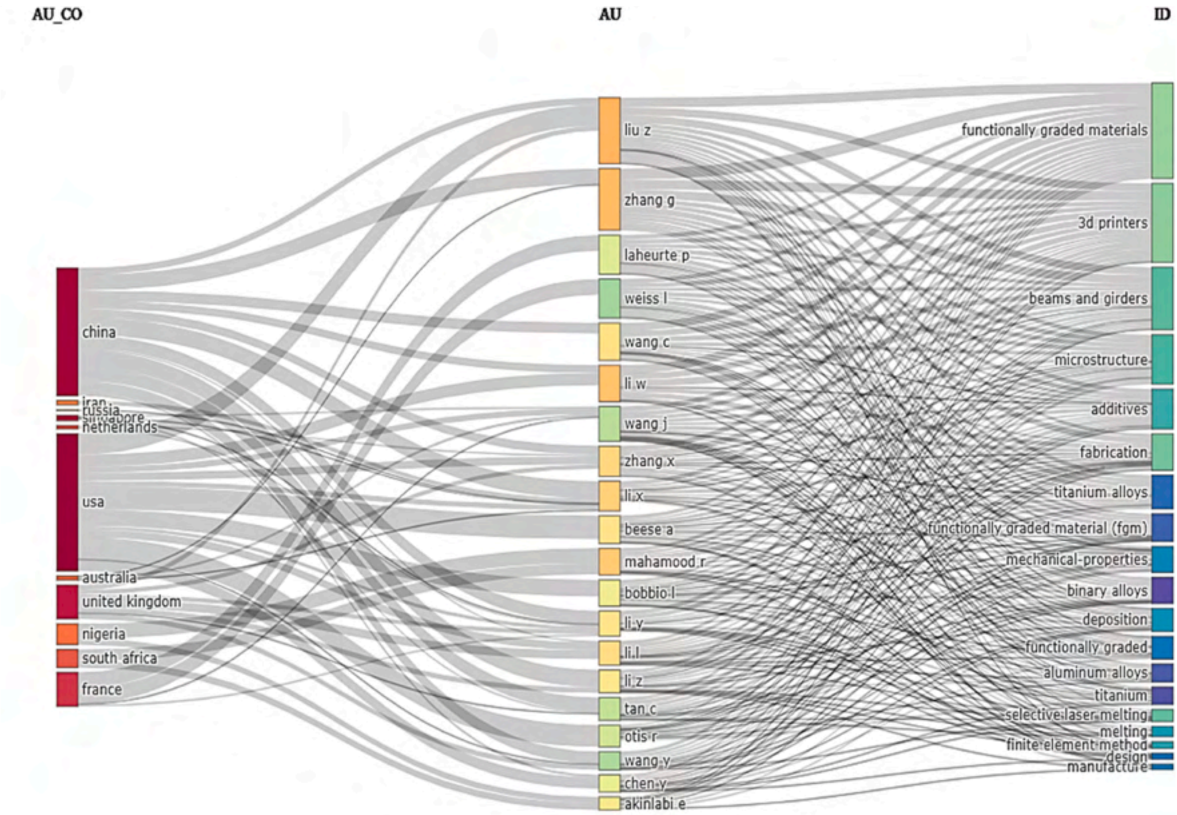


Fig. 4. Trends in the annual number of publications and forecast.

market demand is MMAM for specific industrial applications [47].

A three fields plot of top authors and countries based on the popular keywords in MMAM research was plotted (Fig. 5). This illustration is based on the more well-known Sankey diagrams [42]. The size of the boxes is related to the frequency of occurrences [44]; it can be postulated that the United States has the most publications in the domain of multi-materials research, and its researchers write more on “electronic packaging” “finite element method” and “fibre” is also a popular topic among MMAM academics in the United Kingdom and Japan, while “electronic packaging”, “fibres” and “designs” are popular topics among MMAM researchers in China. “flexible electronics and fibres are also common topics amongst German scholars. The keywords



AU_CO = Author Country, AU = Author names, ID = Keywords

Fig. 5. Three field plot of Authors, author country, and keywords.

"microelectronics" and "fibres" are popular among Singaporeans, whereas "design" and "ceramic materials" are popular among scholars from the Netherlands. The keyword that is related to Korean scholars is "fabrication". All the leading coutries with research focused on MMAM are among the top manufacturing countries in the world. United state and China are top two leading counteries in electonic components manufaturing [49]. This is in line with the huge manufactured electronic products supplied across the globe by these two countries. The literature also reveals that USA, China, and Japan are the top three leading countries that spend a large portion of their GDP on research and development (R&D). In 2018 the USA spent 502.9 billion dollars, China spent 408.8 billion dollars, and Japan spent 170 billion dollars on R&D funding [50]. It could be concluded that as the result of the huge financial investment in the R&D of MMAM in the above-mentioned countries, the researchers in these countries contribute significantly to the innovation/manufacturing of MMAM electronic products, leading to a high number of research outputs.

AU_CO = Author Country, AU = Author names, ID = Keywords.

The global production of publications in MMAM distribution (Fig. 6) demonstrated that the United States of America (USA) has a very high interest in MMAM research (282 publications) and followed by China (82 publications). The USA clearly has a unique interest in multi-materials printing of electronics than the rest of the world due to the huge difference observed between the USA and the rest of the world in terms of the number of publications.

The global network structure (Fig. 7) shows that cross-continent collaborative relations are becoming more frequent; most such collaborations occur between the USA and many nations such as China, Japan, Korea, Germany, Italy, the UK, Iran, Brazil, Canada, Israel, Mexico, Netherlands, Oman, Poland, Saudi Arabia, South Africa, Turkey and Ukraine. Also, the second top collaborator (the United Kingdom) collaborated with Italy, Austria, Canada, Germany, Iran, Netherlands, Nigeria, Oman, Slovakia, Turkey, and Ukraine. The top collaborations are between USA and Korea. The least collaborations emerged from Africa.

3.4. Most relevant sources

The most relevant sources that churned out publications in MMAM were also examined. The top 20 journals collectively published 23.21% of all publications, demonstrating a fairly dispersed distribution. It may be seen from Fig. 8 that the top journals include Additive Manufacturing, Materials Science Forum, Advanced Materials, Proceedings - Electronic Components and Technology Conference, Advanced Functional Materials, Microelectronics Reliability, International Journal of Advanced Manufacturing Technology, Journal of Micromechanics and Microengineering, Proceedings of Spie - The International Society for Optical Engineering, Advanced Materials Research, Eccomas 2012 - European Congress on Computational Methods In Applied Sciences And Engineering E-Book Full Papers, Micromachines, Advanced Materials Technologies, IEEE Transactions on Components Packaging and Manufacturing Technology, IEEE Transactions on Dielectrics and Electrical Insulation, Materials Research Society Symposium Proceedings, Materials Science and Engineering, Microelectronic Engineering, Nanotechnology, and Optics Infobase Conference Papers. These are leading journals in the field of AM.

3.5. Bradford's law

The source growth is confirmed by Bradford's Law analysis (Fig. 9). Bradford's law [51] has been used to determine which journals are the most important on a specific topic. Bradford's law demonstrates a pattern in how a subject's literature gets disseminated through journals. "If scientific journals are arranged in order of decreasing productivity of articles on a given subject, they may be divided into a nucleus of more specifically devoted periodicals and several other groups of zones containing the same number of articles as the nucleus, according to Bradford's law of scattering" [52,53]. Bradford's law is used to determine the most important sources in a particular field of study. For instance, Neelamma and Gavisiddappa [54] applied Bradford's law to analyzed the research output performance of Crystallography, which is covered in

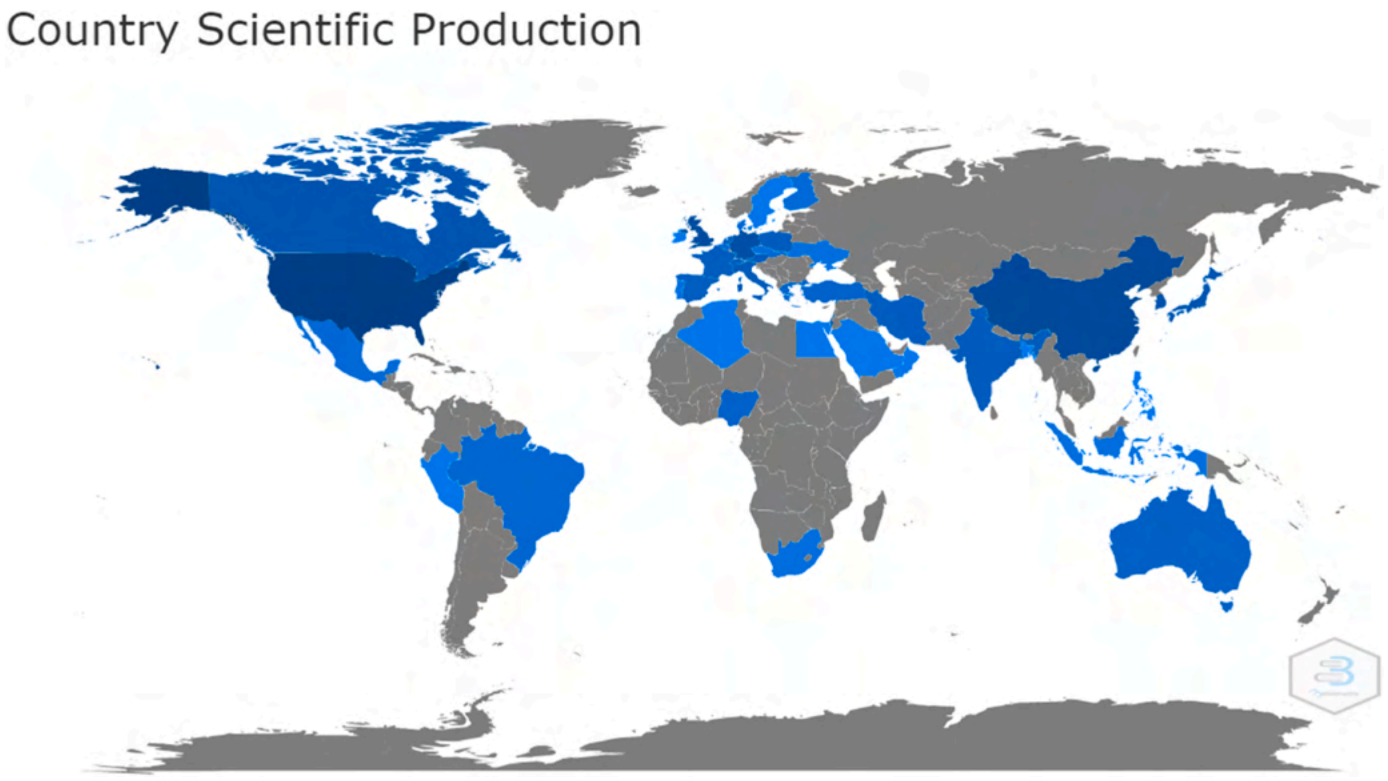

Country Scientific Production

Fig. 6. Country scientific production.

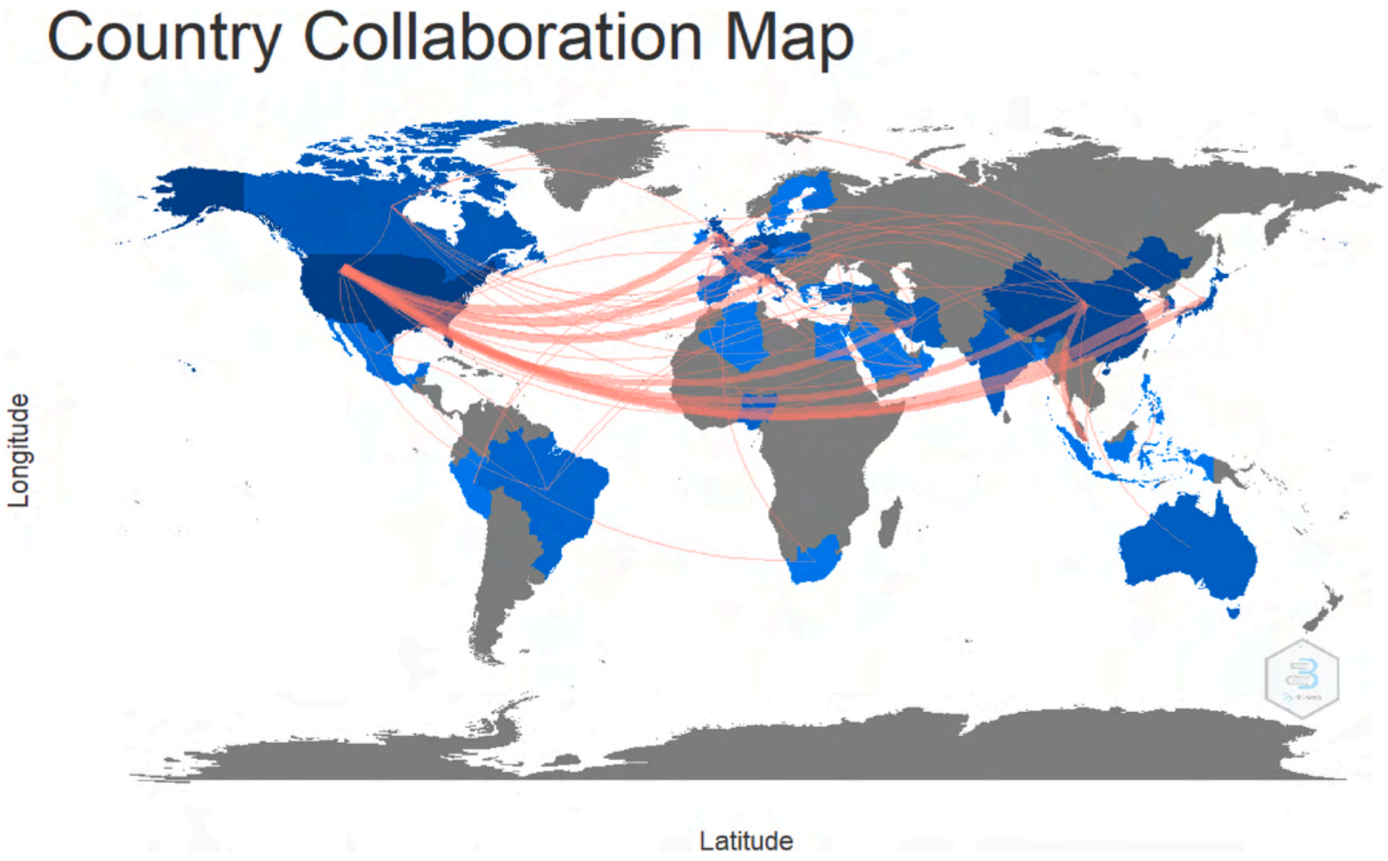


Fig. 7. Country collaboration map.

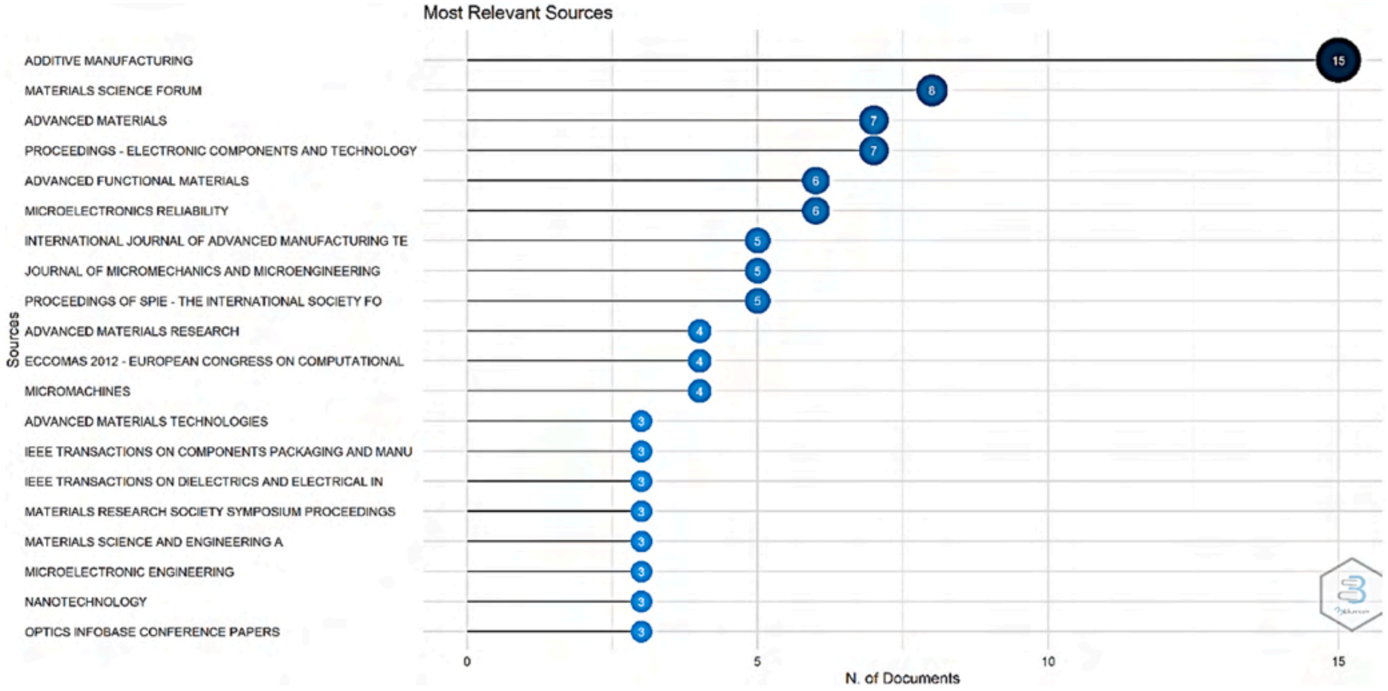


Fig. 8. Most relevant sources.

the Web of Science online version database from 1989 to 2013. They concluded that Bradford's law fitted the data and were able to show the major sources of impact to the field. Out of 291 sources (Table 1), 37 are core to the publication of multi-material additive manufacturing research.

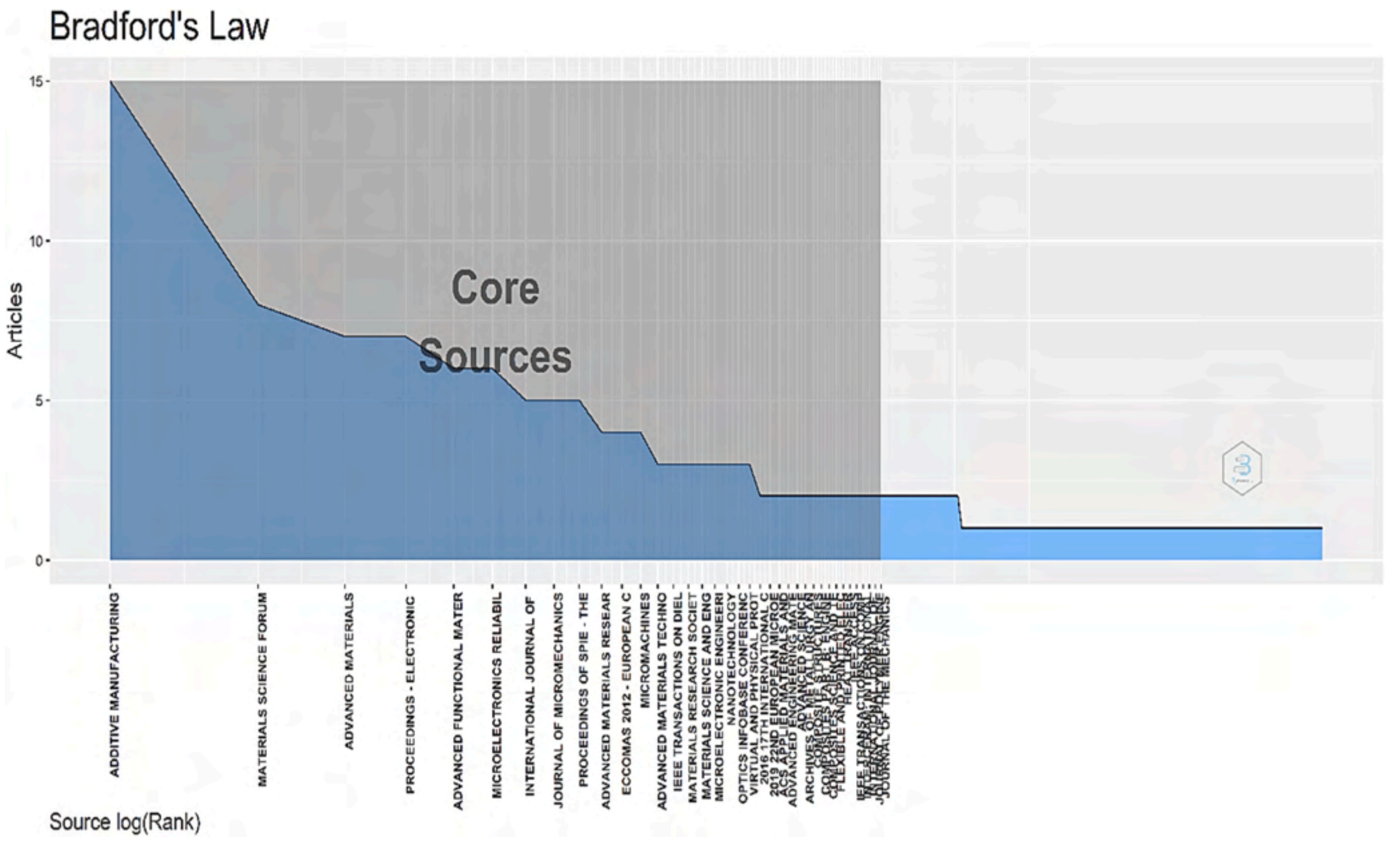


Fig. 9. Bradford's law.

3.6. Source growth

Fig. 10 shows the source growth over the years for the top five sources. The conference on electronic components and technology started presenting contributions on MMAM in 1998 with two publications, followed by the Materials science forum, which started producing

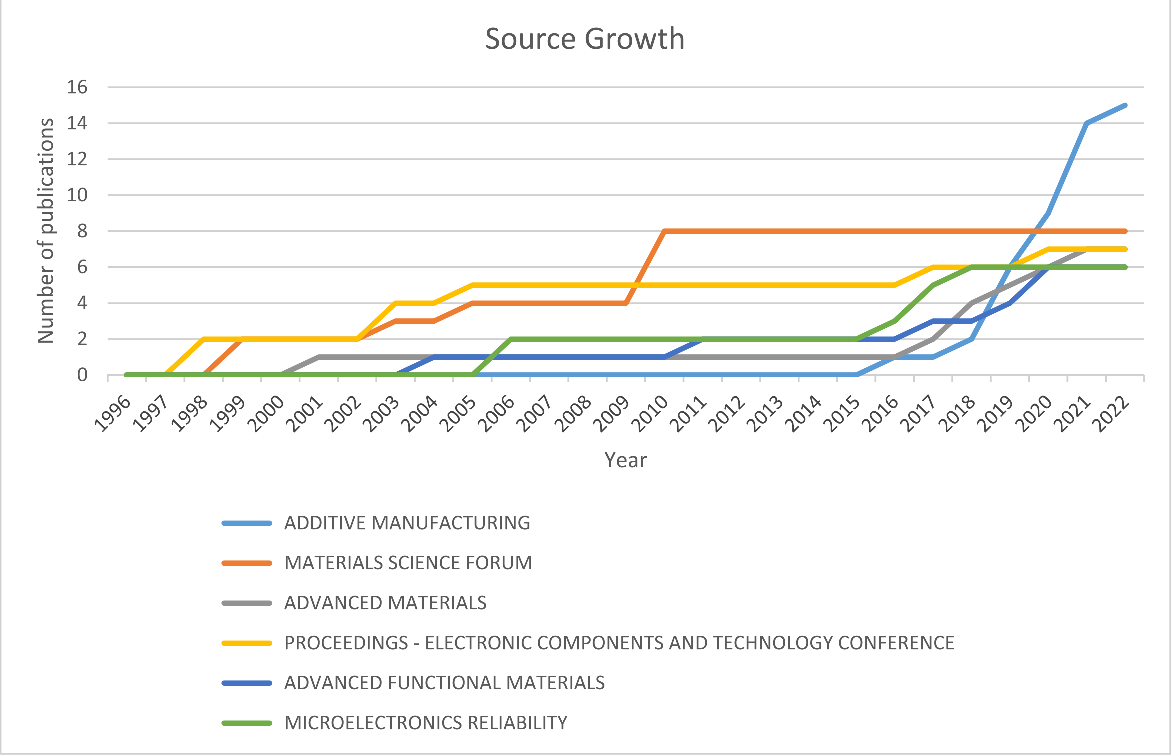


Fig. 10. Source growth.

papers in 1999. Advanced materials also started churning out contributions in 2001 and then Advanced functional materials in 2004. Microelectronic reliability started in 2006. The Additive Manufacturing journal began contributing in 2016 but has rapidly become a very prominent source in MMAM with an annual growth rate of 52.78%.

3.7. *Most relevant authors*

Many authors have made significant contributions to the advancement of MMAM research since its inception. The goal of this section is to present some of these authors based on information from Scopus and WoS regarding the number of papers they have published. Some of MMAM's most well-known researchers appear in these results. However, due to the unique nature of the ranking, numerous other well-known authors may not appear. It is challenging, for example, to include authors who have published their research in other databases. As a result of this ranking, some notable scholars in MMAM may be identified, although it is crucial to highlight that many other authors could have surfaced based on different criteria. It is possible to rank authors based on the number of citations they have received. Both strategies have been utilized in earlier studies in the literature. For example, Hsieh and Chang [55] opted to rank writers according to the number of publications. Fig. 11 depicts a list of the top twenty (20) authors with the greatest number of publications. They include Wang J., Wang Y., Chen L., Li Y., Oguntala G., Sobamowo G., Sorin F., Abd-Alhameed R., Abouraddy A., Fan X., Lee J., Madenci E., Na N., Qu Y., Wang X., Wang Z., Wei L., Zhang H., Zhang L., and Bailey C.

3.8. *Top-authors' production over time and articles*

The top authors' production over time is a combination of the production of articles and total citations over the period in which their contributions have been relevant. Fig. 12 shows the time when the top twenty (20) authors first contributed to the field of MMAM of electronic components in Scopus and web of Science indexed journals, their contributions over the years, and the length of years that they have contributed. The length of years is represented by the orange line, and the size of each dot indicates the contributions in that particular year. It may be noted, for instance, that Lee's [56] first contribution was in 1998 and has remained a relevant contributor till 2017. Chen et al. [57–59] have also contributed since 1999 and have been consistent till 2020. However, Liu Sorin and Qu started their contributions later in 2017 but have produced many publications hence the deep blue dots along the years 2021 and 2020, respectively.

3.9. *Keyword analysis*

This section presents an analysis of the keywords in the publications of MMAM. First, the word cloud is discussed, then the word growth, trending topics and co-word analysis. It is necessary to analyze the keywords because it provides an idea about the major themes that are being discussed in the research area [60]. The Word cloud (Fig. 13) shows the words that have been used frequently in the research area. The more prominent the word, the more frequent its application has been. The keywords analysis produces two distinct patterns. There seems to be a renewed interest in the research area since 2015, as already presented in Fig. 4 above. It would be interesting to identify the keywords that were prominently used prior to 2015 and after 2015. Therefore, the first-word cloud shows the keywords between 1996 and 2014 and the second one shows between 2015 and 2022.

The word clouds (Fig. 13) show the differences and similarities between the conversation prior to and after 2015. First, the term multi-material, which is a major keyword, seems to be prominent in both year groups but is more prominently used after 2015. After 2015, the keyword 3D printers became more prominent. It is worth noting also that terms such as electronic packaging, finite element method, composite materials, electronic structure, and ceramic materials were more prominent before 2015. However, beams and fabrication, deposition, microstructure, microelectronics, flexible electronics, and fibres are characteristic of publications that were churned out after 2015. This shift in the word cloud after 2015 could be due to the different evolution phases of the AM landscape as presented in Fig. 14.

Although it is speculated that the concept of AM started in 1945 [61, 62], it was only in the 1980s [43] that the first AM systems were introduced. In the early day machines (FDM, SLA, SLS) were mainly used for prototyping hence the name rapid prototyping. The 1990s saw

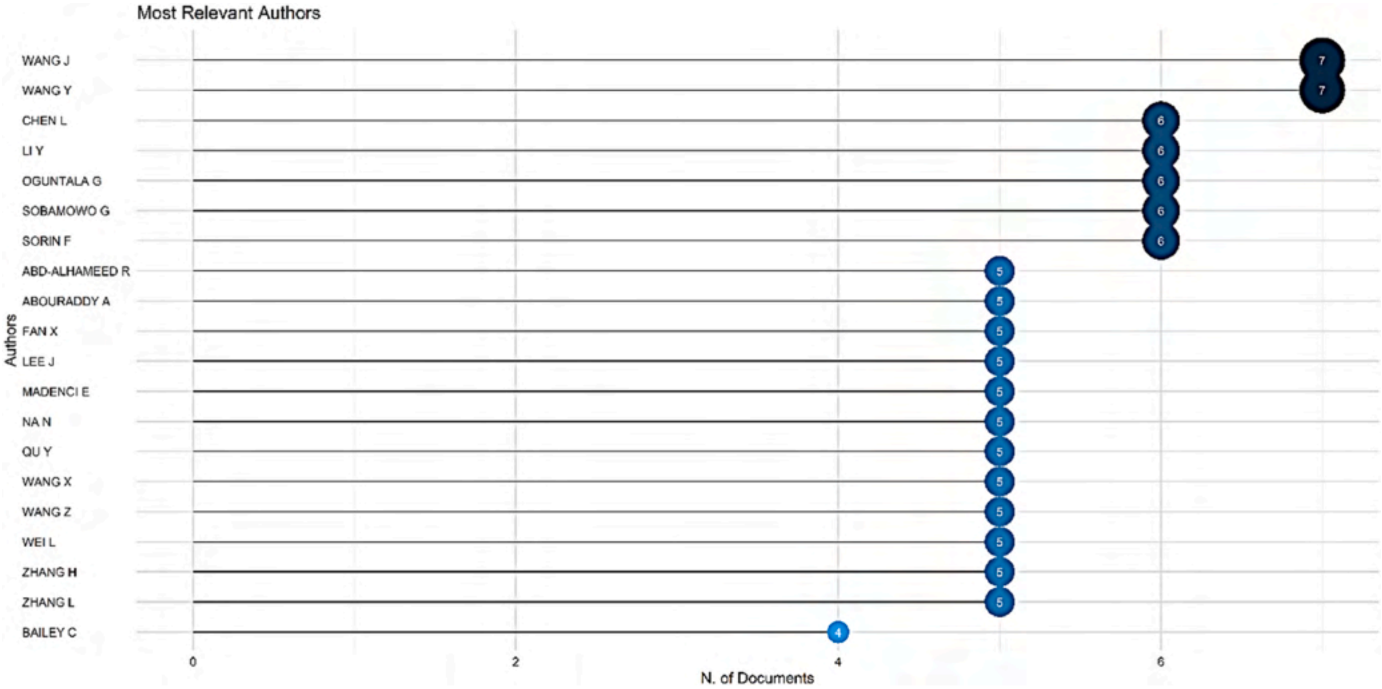


Fig. 11. Most relevant authors based on the number of publications in Scopus and WoS.

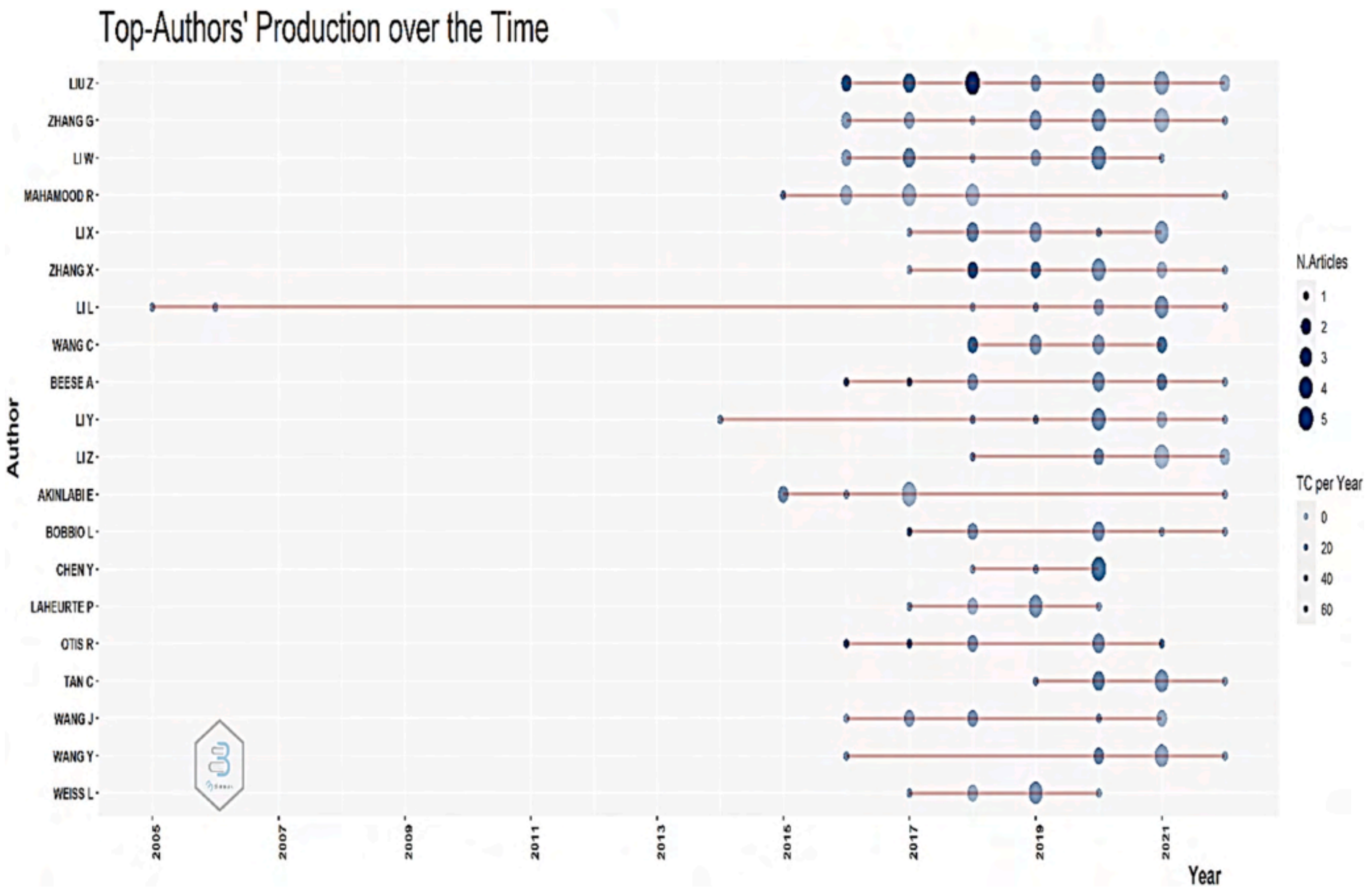


Fig. 12. Top authors' production over time.

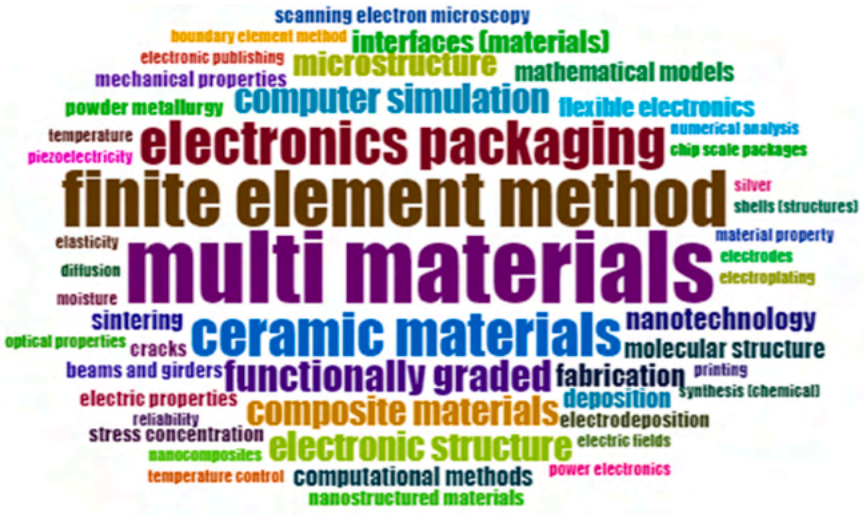
the emergence of computer-aided design (CAD) software that improved the performance and the efficiency of AM systems to begin to produce end-user products. As presented in the first segment of the word cloud (Figs. 13, 1996–2014), finite elements analysis and computer simulations were some of the dominant research foci in the 1990s and the early 2000s. Since the initial investment in setting up AM production/research centers is very steep [63,64], most research institutions could not afford the AM machines but rather focused on simulating the process. As the AM systems began to develop and the prices of the older AM machines began to decline, research institutions were able to procure these machines [65,66]. This has opened the window for researchers to simulate and manufacture 3D objects layer-by-layer, hence the dominance of the word 3D printers since 2015 (Figs. 13, 2015–2022).

The MMAM began to emerge in the 2000s, and by 2010, the first MMAM prototypes were produced. As can be seen in the first segment of the word cloud (1996–2014), multi-material emerged as the principal research focus, and the first publications appeared in the archives in 1996 [67]. Since 2015 AM systems have developed and have taken centre stage for producing customized end-user products of intricate geometrical, technical, and enhanced functionalities. As demonstrated by the word cloud (2015–2022), 3D printing (additive manufacturing), and multi-materials are the main research focus after 2015 because, at this stage, the AM systems have attained maturity in manufacturing 3D objects with one material, and the industrial requirements have changed to multi-material fabrication. The results of the word cloud analysis demonstrated that MMAM is the current focus of the AM process. It is empirically proven that AM systems can be used to produce 3D structures of high mechanical integrity. The current industrial demand is the use of multi-materials to fabricate 3D structures with unique properties in strategic locations based on the intended applications of the final products.

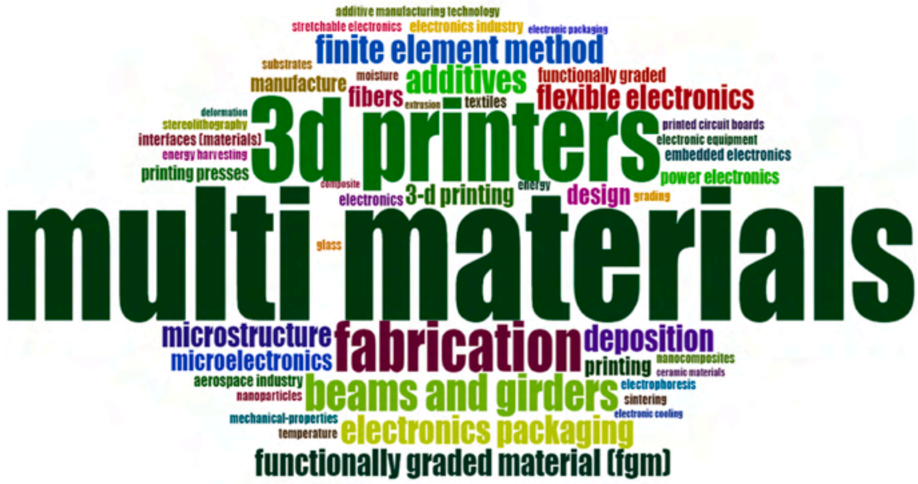
The idea of manufacturing multi-materials components has already been in existence, and the conventional methods were used to produce multi-materials components by rolling, welding, diffusion bonding, powder metallurgy, and chemical vapour deposition [68–71]. These processes were laborious and time-consuming, as presented in Fig. 15. With the conventional methods of manufacturing, it was difficult to control the distributions (material transition from discrete or graded) of different selected materials or compositions of the materials. Due to the layer-wise building strategy, AM has the capacity to precisely control the spatial distributions of materials and thus holds great potential for the design and manufacturing of multi-material structures [72].

3.10. Word growth

Fig. 16 shows the growth of major keywords over the years. The top ten (10) keywords are Functionally Graded Materials, Multi Materials, 3d Printers, Finite Element Method, Fabrication, Electronics Packaging, Beams, Microstructure, Deposition, and Ceramic Materials. Introduced first in 1997 and appearing once each, the keywords *Functionally graded material, Deposition,* and *Ceramic materials* have grown exponentially. *Multi-materials, Finite element method, fabrication,* and *electronic packaging* were also introduced in 1998. Words that were introduced later were microstructure in 2002, Beams in 2008, and 3D Printers in 2013. The rapid growth of the words demonstrated the interest of researchers, industry practitioners, governments, investors, and all other keyholders in the need to produce multi-materials additively. The MMAM technology holds the potential to solve many industry requirements that would improve the quality of life of humanity - which is the ultimate goal of R&D.

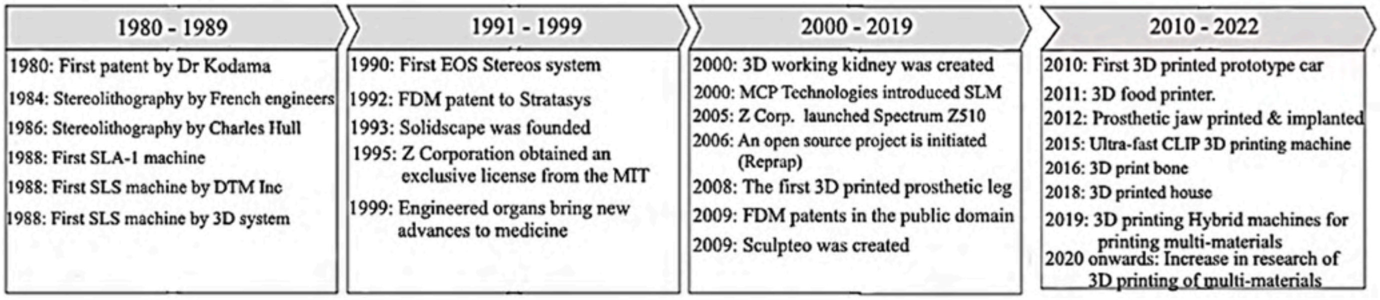


1996 - 2014



2015 - 2022

Fig. 13. Word cloud.



1980 - 1989
1980: First patent by Dr Kodama
1984: Stereolithography by French engineers
1986: Stereolithography by Charles Hull
1988: First SLA-1 machine
1988: First SLS machine by DTM Inc
1988: First SLS machine by 3D system

1991 - 1999
1990: First EOS Stereos system
1992: FDM patent to Stratasys
1993: Solidscape was founded
1995: Z Corporation obtained an exclusive license from the MIT
1999: Engineered organs bring new advances to medicine

2000 - 2019
2000: 3D working kidney was created
2000: MCP Technologies introduced SLM
2005: Z Corp. launched Spectrum Z510
2006: An open source project is initiated (Reprap)
2008: The first 3D printed prosthetic leg
2009: FDM patents in the public domain
2009: Sculpteo was created

2010 - 2022
2010: First 3D printed prototype car
2011: 3D food printer.
2012: Prosthetic jaw printed & implanted
2015: Ultra-fast CLIP 3D printing machine
2016: 3D print bone
2018: 3D printed house
2019: 3D printing Hybrid machines for printing multi-materials
2020 onwards: Increase in research of 3D printing of multi-materials

Fig. 14. Additive manufacturing landscape.

3.11. Trending topics

The trend topics show the trending terms or the most prominent terms that have been used over the years. For simplicity of the diagram, the number of words per year was limited to three each. Fig. 17 shows trending topics from 1998 to 2022. The length of the line shows the period within which the word has been prominent, and the dots show the time frequency, as shown in the legend on the left of the diagram.

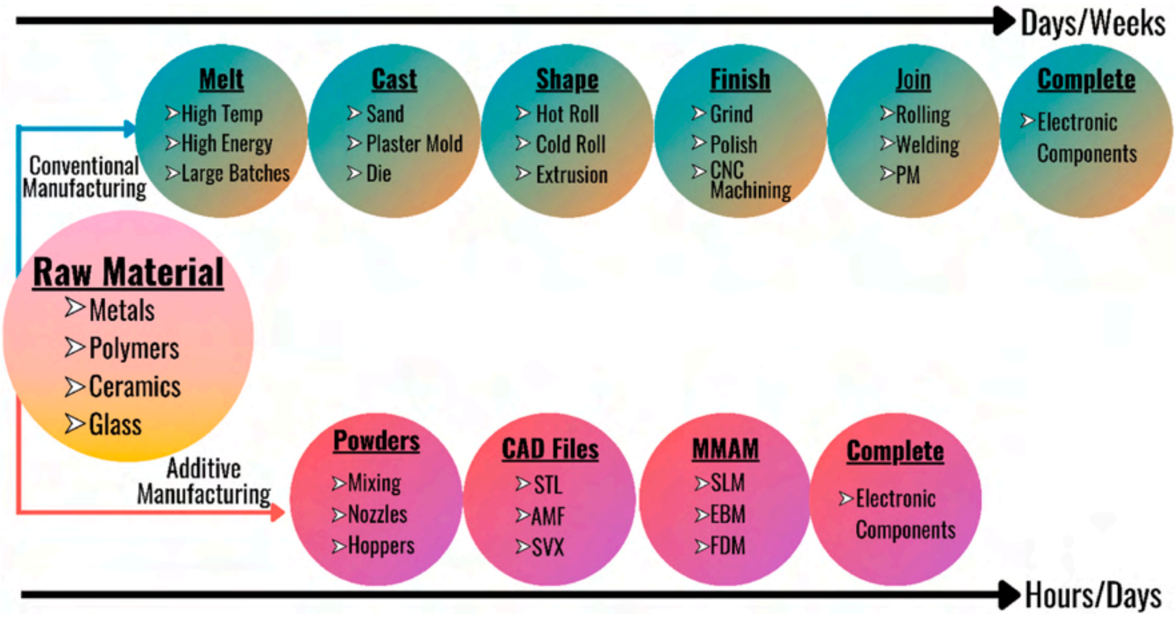


Fig. 15. Process comparison of conventional manufacturing processes versus MMAM process for electronic components.

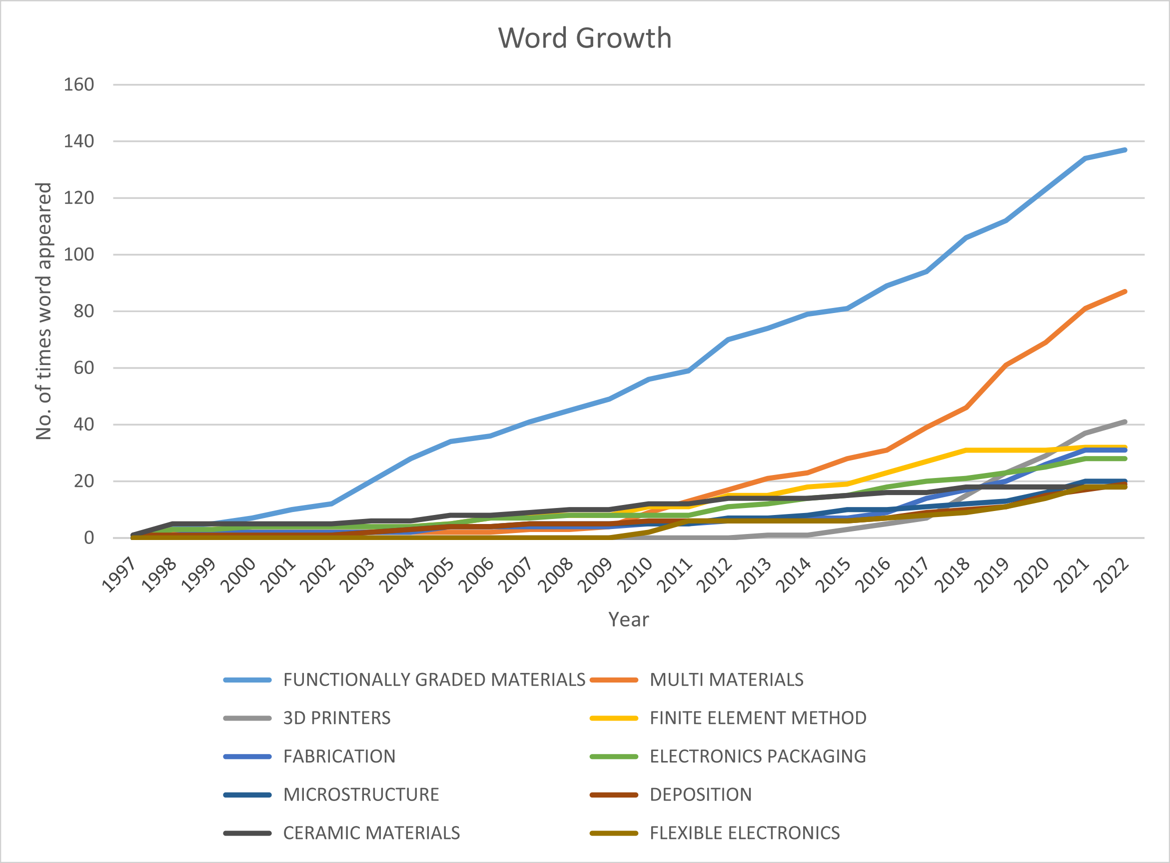


Fig. 16. Word growth.

Focusing on the most prominent words in the past five years, the publications on MMAM have been well focused on words such as microelectronics, printing, deposition, fabrication, multi-materials, electronics industry, 3D printing, energy, additives, functionally graded materials, additive manufacturing technology, grading and most recently, aerospace industry. It is not surprising that the aerospace industry is trending as one of the major areas of research focus regarding applications of multi-materials. The aviation industry is a multi-billion industry, and since the AM process is currently mainly used for high-value engineering products, the aerospace industry is one of its main focuses [47,73]. Using AM systems to produce lightweight near-net structures monolithically has already had a tremendous payoff in the

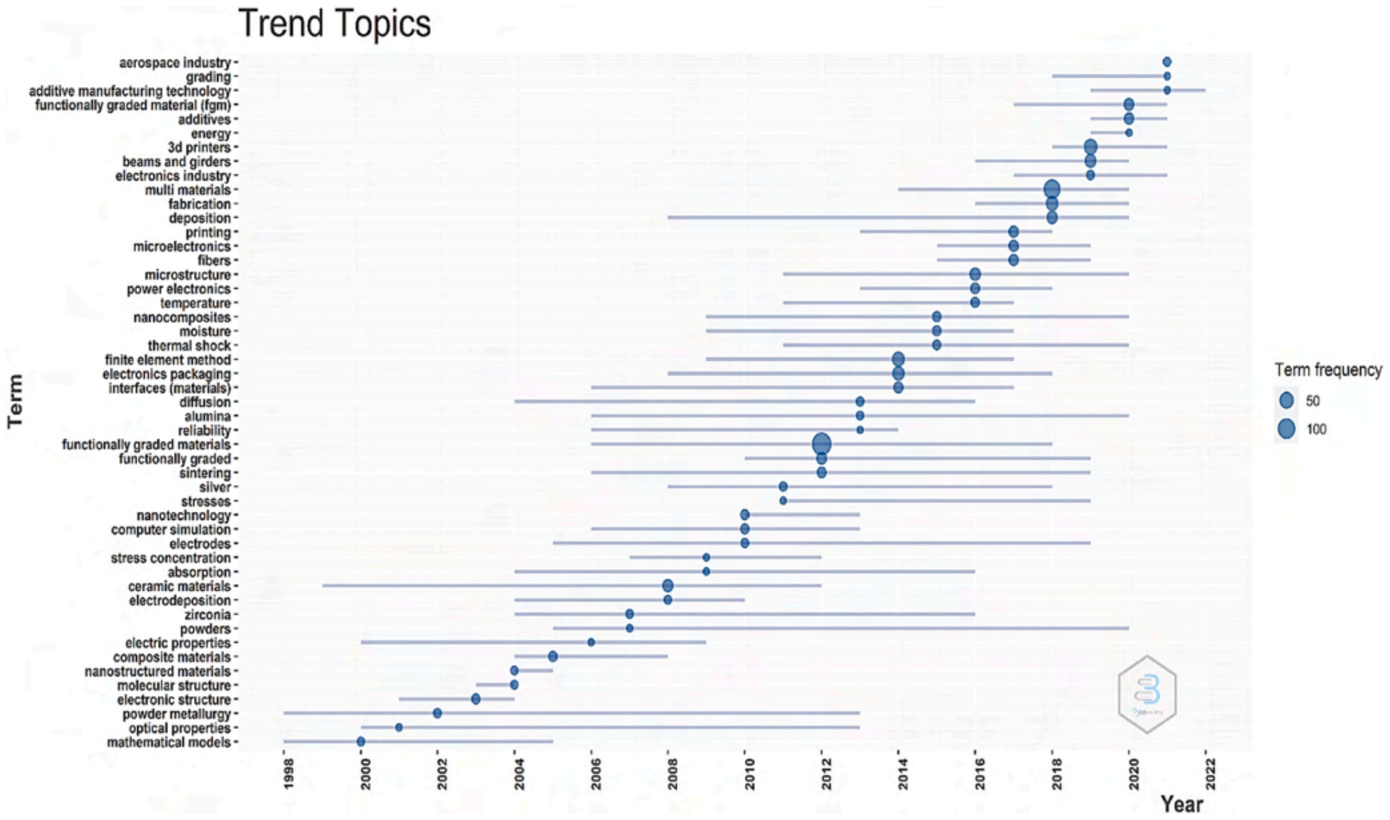


Fig. 17. Trend topics.

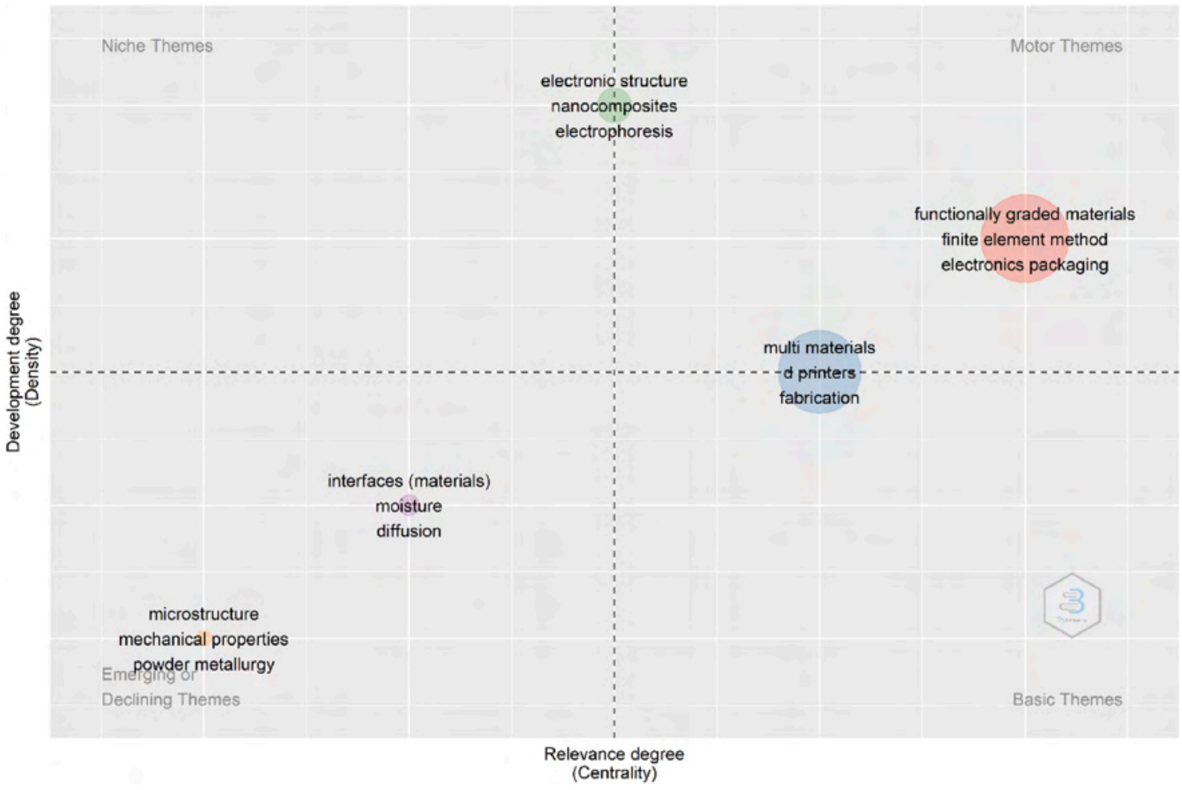


Fig. 18. Thematic map.

aerospace industry [73]. Bewlay et al. [74] reported that General Electric began to explore the benefit of manufacturing near-net structures as an alternative to the initial conventional gravity casting plus machining process to fabricate low-pressure turbine blade that powers Boeing 787 and 747–8 aircraft. It is recorded that the engines demonstrated a 50% reduction in noise, 80% reduction in NOx emissions and great propulsion efficiency of a 20% reduction in fuel consumption as compared with prior engines in its class. Northwest Airlines [63] also reported a payoff of $440,000 on fuel costs for international flights by incorporating additively manufactured parts in their aircraft. With all these unique benefits of using AM technology to produce near-net-shape for the aircraft industry, it is only prudent to go a step further to produce electronic components with multi-materials for specific industrial applications.

3.12. Thematic analysis

By displaying the progression of subjects through time, the thematic map provides insights into the patterns, trends, seasonality, and outliers of study topics. Thematic maps are presented in a more comprehensible way since themes are divided into four quadrants depending on their centrality (on the X-axis) and density (on the Y-axis). The level of connectivity between topics is measured by centrality, which is significant in a certain domain [75]. Density, on the other hand, measures how far a cluster has progressed in terms of intra-cluster cohesion. As classified in Fig. 18, there are four main thematic classifications (Motor themes, basic themes, niche themes, and emerging themes).

Motor themes are topics that are both able to influence the study field and are highly established [75]. The four themes (functionally graded materials, finite element method, electronic packaging and multi-materials) which have emerged as motor themes are pivotal to MMAM. It is almost impossible to discuss MMAM without mentioning these themes or referring to them. These themes have the capacity to influence MMAM research, as they have already done. These are the core established themes that MMAM research revolves around. Research on one of the themes has a direct impact on the other. For example, as the computational power of computers increases, leading to improvement in finite element methods has a direct impact on multi-material/functional graded materials research. Researchers are able to simulate the behaviour of functionally graded materials, thereby having a foreknowledge of the properties before manufacturing the real 3D objects. Such an approach reduces unnecessary try-and-error methods and laborious lab experiments [76,77].

Basic themes (multi-materials, 3d printing, fabrication) are cross-disciplinary themes. By the very nature of AM process, it is a multi-disciplinary technology that involves many fields of study, including optics, laser physics, heat and mass transfer, metallurgy, mechanics, mechanical engineering, materials science, and other fields of sciences as already discussed above. The basic themes cannot be researched without considering more than one field of study. This prompted the need for research collaborations between various experts to carry out comprehensive research on MMAM. As presented in Fig. 7 (Country collaboration map), there are many ongoing collaborations internationally to harness various ideas around the globe to achieve the manufacturing of MMAM.

Niche topics refer to specialized topics among researchers or institutions. For example, based on the South African National Additive Manufacturing Roadmap, each institution has been equipped to build capacity in different yet complementary aspects of additive manufacturing [78,79,80]. Such a niche approach empowers each institution to be specifically strong in a particular area of the AM process. The niche themes in the current studies are electronic structure, nanocomposites, and electrophoresis. There are experts who have specialized in these areas whose main focus is to develop their field of expertise and how they can integrate and work with others within the MMAM fraternity.

Emerging themes are obsolete themes and themes that have the potential for further development. The themes that have the potential for further development need urgent attention to move MMAM technology to the next level. The emerging themes in the current studies include interfaces, diffusion, microstructure, and mechanical properties. Powder metallurgy and moisture could be considered obsolete themes. Powder metallurgy technology has been in existence for more than a century [81]. Interfaces, diffusion, microstructure, and mechanical properties need to be vigorously investigated in relation to MMAM in order to understand the current challenges in the field and future trends.

3.13. Current challenges and future studies

Despite the remarkable success of using the AM systems to produce MMAM electronic components, there are still many outstanding challenges to be addressed, including weak interfacial bonding between different materials, diffusion at the interface boundaries, microstructure, and mechanical properties of the MMAM components, as elucidated in the emerging themes (Fig. 18). It is important to overcome these barriers in order to push the technology boundary of MMAM. Han and Lee [14] reported that in addition to the technical breakthroughs of using multi-materials for manufacturing electronic components additively, there is a need for a fundamental scientific understanding of materials science, reaction kinetics, mechanics, and the thermophysical difference between the different selected materials in order to overcome the technological barriers for MMAM. According to the distribution of dissimilar materials [76], three main types of MM (metals, polymers, and ceramics) are used to produce electronic components additively. These materials have different interfaces (e.g., metal/metal, metal/ceramic, metal/glass, metal/polymer, polymer/polymer, polymer/metal, polymer/glass, polymer/ceramic, etc.); therefore, different technological barriers need to be overcome for each type of interface bonding issues [2]. The literature reveals that metal/metal interfaces [2] are the most common interfaces in the MMAM of electronics components, probably due to the interfacial challenge of producing metal/ceramic, metal/glass, and metal/polymer multi-materials additively. The different atomic bonding that exists among these materials that are used to produce the multi-materials additively is the main challenge. Due to the different thermophysical properties (melting points, thermal absorptivity, specific heat capacity, thermal conductivity, density, coefficient of thermal expansion, phase transformation temperatures etc.) [81], of the various materials that are used to produce the multi-materials electronics components, weak interlayer and intralayer bounding issues such as delamination, porosity at the boundaries of the dissimilar materials, coating defects, interlayer and intralayer cracks has become the main focused of many researchers currently [12,68,82,83]. Most of the studies have focused on the various interlayer printing mechanism to overcome the weak bonding between the different materials. Wang et al. [84] adopted island scanning and inter-layer stagger scanning strategies in the interfacial layers for printing 316L/CuSn10 bimetallic structures using a powder bed fusion AM system. The authors reported a good ultimate strength of 423.3 MPa. The result obtained by Wang et al. [84] is higher than the ultimate strength of 150–300 MPa reported for steel/copper multi-material structures produced via conventional manufacturing methods [85,86]. The interlayer printing strategy was used by Wu et al. [87] to print CuSn10/4340 gear parts and report good interlayer bonding between the two materials. Koopmann et al. [88] investigated the interfacial strength between metal/ceramic structures using 1.2367 tool steel and ZrO2+Al2O3. An adhesion strength of 22 MPa was reported between the 1.2367 tool steel/ZrO2+Al2O3 structures. An investigation by Zhang et al. [89] between metal/glass multi-material structures results in a discrete interface without oxidation at the interlayer phase. There was a gradual transition from ductility at the metal side to brittleness at the glass side.

The microstructure of dissimilar materials at the interface has a decisive effect on its interfacial mechanical properties [90,91]. If the atomic bonds at the interface of the materials are the same as the metal/metal interface, a fusion region is generated at the interface of the materials with a composition gradient variation [92]. The microstructure features such as refined grains and composition gradient at the interfacial joints for metal/metal could improve the interfacial bonds between different metals [93,94]. For materials of different atomic bonds, such as metal/ceramic, metal/glass, and metal/polymer, their interface strength depends upon mechanical interlocking between the materials [95]. Chueh et al. [95] report on metal/polymer interface using PA11 (polyamide powder) and CuSn10. The authors noted that irregular interfaces between the two materials enhance the bonding strength through the mechanical interlocking structures. The melted PA11 penetrates the CuSn10 and attaches along the rough side surface of CuSn10 during the scanning process, enabling the PA11 to adhere strongly to CuSn10 via mechanical interlocking.

Despite the seeming success achieved in producing MMAM components, the issues of interfacial bounding, which have a direct effect on the microstructure hence the mechanical properties of MMAM parts, are still under vigorous research from academics and industry partitioners. Due to the different thermal properties (melting temperature, thermal expansion coefficient, thermal conductivity, etc.) between the various materials – during the AM process, an interfacial defect normally occurs at the interfacial regions making it difficult to produce porosity-free and crack-free interfaces with strong bonding. The difference in the thermophysical properties of the different materials used for MMAM of electronic components could also result in unmelted powder particles at the fusion zones [96,97,98]. The presence of um-melted powder particles at the fusion zones would cause a weak interfacial bond and other defects such as porosities, delamination etc., which would affect the mechanical properties of the final MMAM electronic components. Although the current literature demonstrates that there has been great progress towards the improvement of MMAM of electronic components, issues of interfacial bond, microstructure, and mechanical properties as demonstrated by emerging themes are still not yet solved. There is a need for further research on these emerging themes in order to achieve the ultimate goal of MMAM electronic components with excellent mechanical properties. A suggestion in this regard is onward research on how non-destructive testing methods could be used to qualify the MMAM components for industrial applications.

4. Conclusion

A systematic review approach was adopted to analyze the growth and trends of MMAM research using Scopus and WoS data based. The study reveals that USA, China and Japan are among the top countries that focus on researching MMAM leading to considerable research outputs. The government of the top leading countries conducting research on MMAM spends a large portion of their GDP on R&D funding. The research trajectory of MMAM began to increase exponentially from 2015, when most research units could procure AM systems as the price of AM systems began to decline. Prior to 2015, most of the research outputs focus on the simulation of the MMAM process. The research hype from 2015 has led to the great success in manufacturing multi-materials for electronic applications. The MMAM process has enabled the manufacturing of electronic components of miniaturized sizes, leading to great payoff in weight reduction, fuel consumption, noise reduction, emission of NOx and great propulsion efficiency, especially in the aerospace industry. Hybrid additive manufacturing has emerged as a possible solution to manufacture electronic components with multi-material. From the emerging themes, further research is required to break multi-material interfaces' technological barriers to overcome inter/intra bonding defects.

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. All authors contributed equally.

Declaration of competing interest

The 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.

Data availability

Data will be made available on request.

Acknowledgments

This work is based on research supported by the South African Research Chairs Initiative of the Department of Science and Technology, and the National Research Foundation of South Africa (Grant No. 97994), the Collaborative Program in Additive Manufacturing (Contract No. CSIR-NLC-CPAM-21-MOA-CUT-01), the Manufacturing, Engineering and related Services Sector (merSETA) and Central University of Technology (CUT) MoA: Funding of the Chair in Innovation and Commercialisation of Additive Manufacturing (CICAM), 21 December 2018.

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