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| RESEARCH ARTICLE

Recent Advances in Additive Manufacturing Processes, Monitoring, and Thermal Applications for Advanced Industrial Components

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| ABSTRACT
Additive manufacturing (AM) is no longer just a prototyping technique but has become a serious technology for the production of very complex industrial components with high performance properties, which is still in the process of reaching lightweight construction standards. Additive manufacturing (AM) is now no longer only a prototyping technique, but has become a serious manufacturing technique, which is still being developed to reach lightweight construction standards, in order to produce very complex components with high performance properties. This review summarizes the latest advances of AM processes, in process monitoring, in thermal applications, materials characterisation and in industrial implementation. Significant progress in powder bed fusion, directed energy deposition and associated deposition technologies have facilitated the processing of complex architectures, high melting point materials, multi material structures, and functionally graded architectures. Specific focus is on thermal management by conformal cooling channels, optimized heat exchangers and integrated thermal structures in aerospace, turbine, automotive, medical and energy industry. Machine learning and predictive modelling, in combination with the digital twin and closed loop control, are demonstrated to be opportunities for adaptive parameter optimisation and increased process certainty. Thermal analysis, X ray diffraction, electron backscatter diffraction, metallography and porosity assessment are also deemed as essential tools for establishing links between processing conditions, microstructure, thermal behaviour, and final component performance. Although great strides have been made, there are still limitations in the form of residual stress, porosity, thermal distortion, processing variability, high equipment costs, post processing requirements, scalability, data accessibility and certification.

| KEYWORDS

Additive manufacturing; In process monitoring; Thermal management; Microstructure characterization; Intelligent manufacturing.

| ARTICLE INFORMATION

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1. Introduction
In recent years, there has been a tremendous progress in additive manufacturing (AM) including major process technology advances, process monitoring and post processing, thermal management, characterization of materials, and quality control for advanced industrial parts. The field has expanded into creating reliable, high performance and increasingly more complex parts for the aerospace, automotive, energy, medical and other industrial markets, as well as for rapid prototyping [Karunakaran, 2010]. Such change has been facilitated by the ability of AM to reduce manufacturing material waste, shorten manufacturing time, reduce some of the post processing

requirements, and produce geometries, tailored microstructures and integrated functional features that are difficult or impossible to achieve through conventional manufacturing processes. Manufacturing engineering, materials science, digital manufacturing, computational modelling, sensing technologies and artificial intelligence have thus brought AM into the focus as an important part of next generation manufacturing [Saxena, 2018]. The metal AM processes of powder bed fusion (PBF), directed energy deposition (DED), and arc based deposition processes are important technological foundations of this development. PBF processes, such as electron beam melting, selective laser melting, and direct metal laser sintering, enable the fabrication of intricate components and offer high geometric freedom and feedstock efficiency for metallic materials. However, performance is highly dependent on process parameters and powder, as well as thermal and environmental conditions [Hossain, 2024]. Defects such as porosity, cracking, lack of fusion, balling, distortion and excessive surface roughness can be encountered if the laser or electron beam power, scanning speed, hatch spacing, layer thickness and scanning strategy are improperly combined. The on-going research consequently is shifting towards understanding the process physics and setting up process window with process consistency for the consistent part quality for various materials and manufacturing systems [Pragana, 2021]. DED has also been gaining significant interest for its ability to process large parts, repair processes, material deposition on existing products and functionally graded or multi material architectures. Compared to PBF, DED has the potential to manufacture larger components, facilitate the addition of material, and enable material composition to be changed during manufacturing. These properties have a significant impact on the application of DED, especially in the aerospace industry, energy, tooling, and repair [Lauwers, 2014]. The relatively high deposition rate and the ability to use conventional welding techniques make Arc based AM approaches promising routes for large scale deposition of metals. However, these issues of dimensional accuracy, thermal distortion, residual stresses, surface quality and process stability are still not well understood. Thermal monitoring is especially crucial, since AM is essentially governed by very localized and rapidly changing heat transfer phenomena [Sebbe, 2022]. The thermal gradient and the cooling histories are steep and complex, respectively, and they affect the formation of the microstructure, residual stress, distortion, phase transformation and mechanical properties when repeated melting and solidification occur. The size and temperature profile of melt pool can therefore be used as good indirect indicators of process stability and defect formation. Thermal imaging and infrared measurements can detect abnormal heat accumulation, inadequate melting, overheating and differences in cooling [Krimpenis, 2023]. This type of data can then be incorporated into models of the processes to better predict the thermal history and microstructural evolution.

Significance: This review examines advances integrating AM, thermal management, monitoring, characterization, and intelligent control for reliable high performance industrial components.

2. Additive Manufacturing Process Advances, Monitoring, and In-Process Quality Assurance

The recent developments in additive manufacturing (AM) have been aimed at increasing the processes capabilities and quality of the manufactured components, new material systems, and increasingly more complex architectures [Merklein, 2016]. The advantage of AM is the ability to selectively deposit materials in a layer by layer or particle by particle fashion in line with digital models, with no need for traditional moulds and significant freedom of component design. It is possible to develop a complex component with a high degree of freedom in geometry, using computer aided design, process simulation, slicing, deposition, and post processing software to support the entire manufacturing process [Chattopadhyay, 2024]. It is this ability that allows the creation of complex external and internal forms, light structures, functional-integrated elements, and parts that offer a better strength to weight ratio. Many AM processes include the features of high energy input and fast cooling rates that can also affect the material's solidification structure and phase transformations, offering opportunities for the customization of material properties during AM processes [Praveena, 2022]. Powder bed fusion is an emerging technique for manufacturing high performance metallic parts, especially for complex shapes and challenging materials, which is known as laser based powder bed fusion. The processing of tungsten and other high melting point materials has stimulated a great deal of development due to the requirement to overcome several difficulties related to the high melting temperature, thermal conductivity, brittleness and thermal gradient sensitivity of these materials [Jakimiuk, 2024]. In AM, the rapid melting of the tungsten powder occurs in a small melt pool and it then nucleates and solidifies into grains. The control of heat input has now emerged as a key issue in the development of the process, as it directly influences the melt pool size, flow, solidification pattern, defects, and surface quality [Chénier, 2023]. Depending on the energy density and processing conditions, the melt pool can be in conduction mode or switch into keyhole mode. The conduction mode typically results in a stable melt pool with the heat transferred mainly by conduction in the surrounding material.

3. Thermal Applications and Thermal Management of Advanced Industrial Components

The additive manufacturing (AM) has opened up novel options for thermal management in high performance industrial components by making it possible to manufacture complex geometries that are difficult to obtain through classical manufacturing methods [Hossain, 2023]. The capability to create components layer-by-layer, based on digital models, makes it possible to embed internal structures, complex channels, lattice structures, optimized heat transfer surfaces directly within a component. These are very useful for heat exchange, temperature control, light-weight and miniaturized components such as turbine parts, combustion components, energy equipments and so on. One of the most important thermal applications of AM is the development of advanced heat exchangers (Figure 1) [Marques, 2023]. In the conventional manufacturing industry, the complexity of the internal passage is limited by the simple geometry of the internal structure, which can be machined or cast, or connected through welding or drilling. Many of these geometric limitations are eliminated with AM, allowing for the creation of interconnected channels, curved passes, lattices, and topology-optimized heat transfer surfaces (Table 1). The design flexibility allows for higher heat transfer surface, better fluid mixing, smaller volume of components and possibly higher overall thermal efficiency. Another significant application for AM is conformal cooling [Jayawardane, 2023]. Cooling channels are typically simple in conventional manufacturing, and must keep a proper distance from the external surface due to machining and tooling constraints. AM enables the cooling paths to more closely follow complex component geometry. These conformal channels can help to achieve a more even temperature distribution and minimize localized thermal concentrations. This is especially important for turbine blades and other high-temperature parts where the thermal stresses, fatigue life, oxidation, and reliability of the part can be strongly influenced by the temperature gradients [Mechete, 2023]. Additionally, AM allows for integrating thermal management into the design of a part. Cooling channels and heat transfer features can be fabricated as part of the actual building structure rather than manufacturing a separate cooling system, and then installing it. But, if it is to be implemented reliably, the input of energy, the thermal history, the condition of the material, the surface characteristics, the residual stress and post processing have to be carefully controlled. Embracing these developments, the future of AM is likely to see even greater integration with computational thermal modelling, advanced monitoring and intelligent process control, leading to a greater capability to design and produce parts with precisely controlled thermal attributes, enhanced durability, reduced weight, and greater energy efficiency [Jung, 2023].

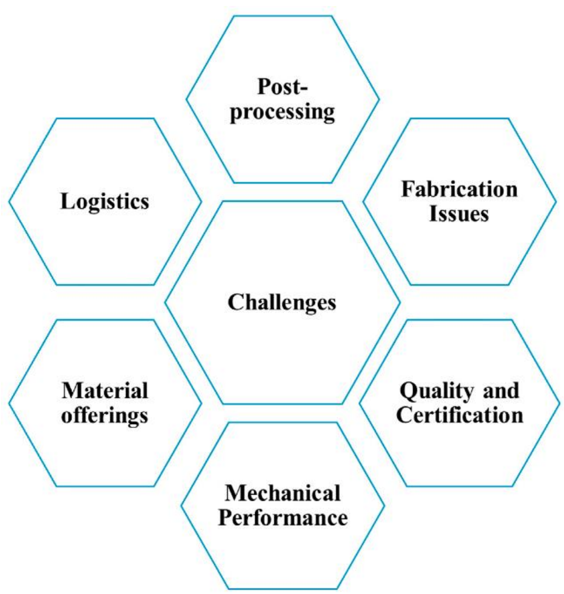

Figure 1. Additive Manufacturing Applications in Mission-Critical Operations [Joghan, 2023]

Table 1. Additive Manufacturing Processes and Their Industrial Applications

AM process	Main characteristics	Major advantages	Industrial applications	Reference
Powder Bed Fusion (PBF)	Layerwise melting of powder using laser or electron beam	High geometric freedom, efficient material use, ability to fabricate intricate components	Aerospace, automotive, energy, medical applications	[3], [4]
Laser Based PBF	Selective melting of metallic powder using a laser	Suitable for complex shapes and challenging materials	High performance metallic components	[11], [12]
Directed Energy Deposition (DED)	Material is deposited and melted simultaneously	Suitable for large components, repair, material addition, and composition changes	Aerospace, energy, tooling, repair	[5]
Arc Based AM	Metal deposition using arc based/welding approaches	High deposition rate and suitability for large scale deposition	Large industrial metal components	[5]
Electron Beam Melting	Powder is melted using an electron beam	Enables fabrication of complex metallic structures	High performance industrial components	[3]

4. Materials and Microstructure Characterization, and Emerging Technologies

The basic character of materials, their phase constitution, microstructure and defect structure plays a fundamental role in understanding the thermal behavior and long term stability of parts manufactured by AM. The thermal response of the component will depend on the processing parameters, as well as on the intrinsic properties of the feedstock material and the microstructure produced by the very fast melting and solidification of the powder during the LPBF process [Prasad, 2024]. These relationships between powder properties, processing parameters, microstructural development, thermal behavior and final part function, can, therefore, only be attained by extensive characterization. These relationships are especially critical when the industrial component is subjected to repeated thermal cycling, high temperature or tough mechanical stresses. The understanding of the behavior of AM materials during processing and service requires the use of thermal characterization techniques [Du, 2016]. Important thermal properties like melting behaviour, phase transformation temperatures and specific heat capacity can be determined by the use of a differential scanning calorimeter (DSC). The results from these measurements can be used during thermal simulations and to optimize processes. Another method of measuring thermal diffusivity and thermal conductivity is laser flash analysis (LFA). The combination of DSC and LFA gives complementary information which can be utilized to determine the effect of powder properties on the heat transfer in AM components, or the effect of processing conditions [Loyda, 2023]. Standardized measurement procedures are especially useful because it gives an ability to more reliably compare thermal properties of different materials, powder batches, and manufacturing systems.

5. Industrial Applications and Case Studies of Additive Manufacturing

Additive Manufacturing (AM) is gaining traction in the industry due to the growing need for dependable production, efficient material usage, online process control and intelligent control. AM is no longer just a prototyping technology, but has matured into a manufacturing technology to create functional parts for challenging industrial applications [Hossain, 2023]. Supporting this transition, the growing integration of in situ sensing, process analytics, automated parameter adjustment, and advanced computational modeling offers increased process consistency, while minimizing risks related to manufacturing defects. In current industrial AM systems, continuous monitoring is being explored as a key process for ensuring production quality. Process variables such as temperature, melt pool characteristics, radiation intensity, deposition geometry and others can be measured using sensors during the fabrication process [Soe, 2024]. They can be compared against pre-defined process limits or expected operating conditions to detect abnormals. If there are deviations, corrective measures could be taken by tuning parameters like laser power, scanning speed, deposition rate, or material flow. These systems can help to detect failures early in the manufacturing process, before the components are finished, which can save material waste and increase production efficiency [Zhu, 2013]. One of the most important areas of industrial AM applications is the aerospace industry, where significant benefits can be found in weight reduction, geometric complexity, and thermal management. Mechanical components of aircraft and propulsion systems have to sustain high mechanical integrity under severe thermal and aerodynamic environment. Traditional manufacturing processes often has significant restrictions in terms of internal geometry, especially for cooling systems and light weight structures [Flynn, 2016]. However, these limitations are overcome with AM by providing complex internal passages, lattice structures, topology optimized geometries and integrated cooling architectures are possible to be created directly within components.

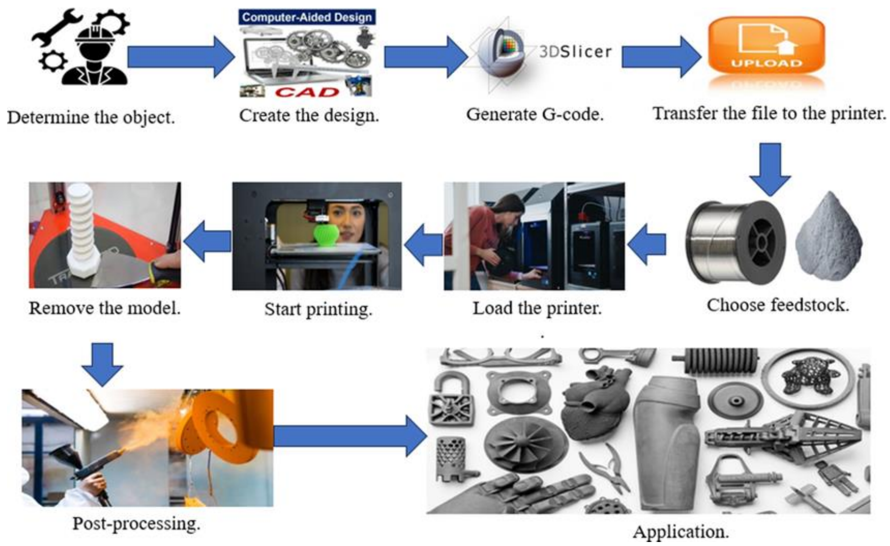

Figure 2. The International Journal of Advanced Manufacturing Technology [Hollister, 2004]

6. Limitations and Future Outlook of Additive Manufacturing

Though the additive manufacturing sector is growing fast, there are still several technical, economic, operational and regulatory hurdles that slow the sector down for large scale industrial adoption of AM. As AM systems grow more complex, they require greater control over thermal behaviour, defect formation, microstructural evolution, data interpretation, and process reproducibility [Lalegani, 2022]. While significant advances are being made, improvements are needed throughout the manufacturing process to bring the transition from demonstrating on laboratory scale to reliable, industrial production. The accurate characterization of the melt pool and thermal conditions during fabrication is one of the major challenges (Table 2). While x ray imaging can give useful information on melt pool boundaries and the internal phenomena, more thermal information, such as cooling rates, temperature gradients, and heat distribution is required to give a full picture of melt pool dynamics [Jiménez, 2021]. A multimodal approach, e.g., high-speed infrared imaging and X-ray imaging, could provide a more complete view of the AM process. Information on surface and subsurface phenomena may be complemented by using different sensing methods, which could enable to better describe melt pool dynamics and defect formation with higher spatial and temporal resolution. But multimodal monitoring adds complexity to the system [Nau, 2011]. Information from multiple platforms may not be easily synchronized due to variations in calibration, data acquisition, spatial resolution, coordinate systems and data processing methods. Standardization of multimodal measurement approaches is therefore important to obtain reliable datasets that can be compared between machines and research environments. One other drawback is the complexity in establishing a relationship between the process parameters and the end part properties in a universal manner [Schuh, 2009]. Laser power, scanning speed and hatch spacing, layer thickness, preheating conditions, and deposition rate will all have a significant impact on the thermal input, and thus on melt pool dimensions, interface movement, cooling rate, microstructure, residual stress, and defect formation. Looking forward, however, the combined development of the various technologies of AM will rely on the resolution of the interrelated challenges. The capabilities to sense accurately, to have reliable thermal models, to have transferable machine learning algorithms, to have standardized data, to have automated control, to have scalable equipment, to have efficient post processing and to have clear certification pathways must all develop in parallel [Williams, 2016].

Table 2. Thermal Management, Challenges and Future Directions

Area	Technology	Role or importance	Main benefit	Reference
Process monitoring	Thermal imaging and infrared measurement	Monitors temperature distribution and cooling behaviour	Detection of overheating, abnormal heat accumulation and inadequate melting	[6], [7]
In process monitoring	Melt pool monitoring	Evaluates melt pool size, temperature and stability	Early identification of defects and process abnormalities	[22], [23]
Thermal management	Conformal cooling channels	Cooling paths follow complex component geometries	More uniform temperature distribution and reduced thermal concentration	[15], [16]
Heat exchangers	Internal channels, lattices and optimized surfaces	Enhances heat transfer and fluid mixing	Potentially higher thermal efficiency and reduced component volume	[14]
Thermal characterization	Differential scanning calorimetry (DSC)	Determines melting behaviour, phase transformations and specific heat	Supports thermal modelling and process optimization	[19], [20]

7. Discussion

Additive Manufacturing (AM) has progressed over the last few years from a technology that was mainly used to prototype to a fully-fledged manufacturing platform for high performance industry parts. The material innovations of the reviewed AM processes, process monitoring, thermal applications, material characterisation, industrial implementation and the intelligent control of the material's state will influence the future development of AM [Kapil, 2022]. Instead of material deposition, quality assessment, thermal management, and component design being done separately, there is ongoing research that seeks to link the processes together, with each process informing the remaining ones. This change is critical for aerospace, automotive, medical, energy, and turbine applications where reliability, dimensional accuracy, thermal stability and repeatability are critical. One of the most important results is the key role of process innovation in the enhancement of AM capability [Hossain, 2022]. Advances in powder bed fusion, directed energy deposition and related technologies have broadened the materials and geometries that can be produced. Laser based powder bed fusion is especially significant for the production of complex internal structures and intricate metal components, while directed energy deposition offers benefits for repair operations, large components and functionally graded materials [Nagamatsu, 2020]. Examples of the growing ability of AM to process high melting point materials like tungsten are shown. The thermal history during rapid melting, repeated melting and solidification of the material results in a unique thermal history which can be used to influence grain formation and microstructure. But there are some difficulties related to keyhole formation, porosity, cracking, residual stress and thermal distortion that come with these advantages [Yue, 2021]. The discussion also shows that heat-input is one of the most influential factors affecting the quality of AM. Melt pool stability and thermal history are determined as a function of laser or electron beam power, scanning speed, hatch spacing, layer thickness and scanning strategy. If too much energy is put into the process, keyhole behavior, vaporization, turbulence and porosity can occur while too little energy can lead to incomplete fusion and weak bonding between the layers. Hence, optimizing the process cannot be achieved based on one parameter only. An appropriate window of processing parameters should be defined while taking into account the interplay of energy input, material properties, geometry, and thermal processing conditions [Sun, 2019]. This is especially important in complex industrial components where the amount of heat that may be generated locally can change significantly throughout the manufacturing process. Another key problem related to the process conditions to the component performance is the residual stress. Thermal gradients that are created by repeated heating and rapid cooling can result in internal stresses, distortion, warpage and cracking. They can be minimized by preheating, optimized scanning strategies, creation of support structures, and control of the energy input in the build and post build heat treatment, but are not easily eliminated [Xu, 2020]. The evidence therefore indicates that residual stress should be managed in a multimitigation approach that includes process optimization, thermal management, process modelling and/or post processing. Thermal applications are one of the most compelling benefits of AM as it enables thermal properties to be integrated into the geometry of the components. AM can create conformal, branching, lattice channels, and topology optimised heat transfer surfaces, which is not always possible in conventional manufacturing. These properties are particularly useful in turbine blades, heat exchangers, aerospace parts and energy systems. Cooling channels can be configured to be more complex in shape to match external surfaces, to achieve better temperature uniformity and to possibly increase the thermal efficiency [Baufeld, 2023]. This is a paradigm shift in design thinking since thermal management is not necessary to be designed as an added system to the component, but can be built into it from the start. However, the effectiveness of these thermal designs rely heavily on material and micro structure generated in the process of manufacture. The heat transfer is affected by the thermal conductivity, phase composition, grain structure, precipitate distribution, porosity and surface morphology [Mertkan, 2022]. Therefore, characterization methods like differential scanning calorimetry, laser flash analysis, X ray diffraction, metallography and electron backscatter diffraction are important to help to correlate processing conditions with thermal behavior. Their simultaneous application is especially useful as no single technique can completely characterize the complex microstructures that can be produced by rapid AM processing. One of the specific features that need to be considered is the porosity, which can also be reducing the mechanical strength and affect the thermal transport [Hossain, 2021]. Optical microscopy can give some useful information regarding pore distribution and morphology, and density-based techniques can give further information on open and closed pores. Examples of differences between measurement techniques show that it is important to carefully characterise the porosity when developing thermal models or quality standards. This highlights the need for multi modal characterization of critical elements in industry. Scalable multi laser systems, intelligent monitoring, digital twins, predictive thermal modeling, adaptive control and standardizing data infrastructures are thus anticipated to be key avenues for research in the future [Liu, 2017]. Digital twins could combine the process parameters, sensor data, simulation results and inspection information into an ongoing digital representation of the component. This may allow for process behaviour deviations between what is predicted and what is learned during fabrication and will aid in predictive quality assurance and lifecycle management.

8. Conclusion

Additive manufacturing is rapidly evolving from a prototyping technology into an advanced manufacturing platform for high performance industrial components. Progress in powder bed fusion, directed energy deposition, thermal management, in process monitoring, and microstructure characterization has improved design flexibility, material efficiency, and component performance. The integration of artificial intelligence, digital twins, predictive modeling, and closed loop control offers further opportunities for real time quality assurance and process optimization. However, residual stress, defects, scalability, post processing, cost, data accessibility, and certification remain important barriers. Continued interdisciplinary research and standardization will be essential for achieving reliable, sustainable, and economically viable industrial AM.

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References

[1] Baufeld B., (2023) Wire electron beam additive manufacturing of copper, *J. Phys. Conf. Ser.*, vol. 2443, p. 012001, 2023. doi: 10.1088/1742-6596/2443/1/012001.

[2] Chattopadhyay S., Mahapatra S. D., and Mandal N. K., (2024) Advancements and challenges in additive manufacturing: A comprehensive review, *Eng. Res. Express*, vol. 6, no. 1, p. 012505, 2024. doi: 10.1088/2631-8695/ad30b1.

[3] Chénier F., Parent G., Leblanc M., Bélaise C., and Andrieux M., (2023) Using a quantitative assessment of propulsion biomechanics in wheelchair racing to guide the design of personalized gloves: A case study, *arXiv*, 2023. doi: 10.1080/10255842.2024.2311324.

[4] Du W., Bai Q., and Zhang B., (2016) A novel method for additive/subtractive hybrid manufacturing of metallic parts, *Procedia Manuf.*, vol. 5, pp. 1018-1030, 2016. doi: 10.1016/j.promfg.2016.08.067.

[5] Flynn J. M., Shokrani A., Newman S. T., and Dhokia V., (2016) Hybrid additive and subtractive machine tools-Research and industrial developments, *Int. J. Mach. Tools Manuf.*, vol. 101, pp. 79-101, 2016. doi: 10.1016/j.ijmachtools.2015.11.007.

[6] Hollister S. J. and Bergman T. L., (2004) Biomedical applications of integrated additive/subtractive manufacturing, in *Additive/Subtractive Manufacturing Research and Development in Europe*, Baltimore, MD, USA: World Technology Evaluation Center, Inc., 2004, pp. 55-62.

[7] Hossain M. A., Badugu D., and Seelu B., (2023) Multi-material and functionally graded additive manufacturing for next-generation mechanical and thermal engineering components, *Brit. J. Multidiscip. Stud.*, vol. 1, no. 2, pp. 11–26, 2023, doi: 10.32996/bjmss.2023.2.2.2.

[8] Hossain M. A., Barman S. C., Pi W., and Islam S. M. T., (2022) A study on hybrid manufacturing systems integrating additive manufacturing and CNC machining for high-precision industrial component production, *J. Mech. Civil Ind. Eng.*, vol. 3, no. 2, pp. 24–41, 2022, doi: 10.32996/jmcie.2022.3.2.4.

[9] Hossain M. A., Bhuiyan M. A. A., Rahman A., and Hasan D. W., (2024) Integration of artificial intelligence for real-time monitoring and process control in metal additive manufacturing systems, *J. Mech. Civil Ind. Eng.*, vol. 5, no. 3, pp. 08–28, 2024, doi: 10.32996/jmcie.2024.5.3.2.

[10] Hossain M. A., Dangol S., Hasan D. W., and Badugu D., (2023) Thermal performance study of additively manufactured compact heat exchangers for industrial energy systems, *J. Mech. Civil Ind. Eng.*, vol. 4, no. 4, pp. 86–103, 2023, doi: 10.32996/jmcie.2023.4.4.9.

[11] Hossain M. A., Pi W., Islam S. M. T., and Lide M. I., (2021) Smart manufacturing framework for real-time process monitoring, predictive maintenance, and quality control in advanced mechanical production systems, *J. Mech. Civil Ind. Eng.*, vol. 2, no. 1, pp. 11–24, 2021, doi: 10.32996/jmcie.2021.2.1.3.

[12] Jakimiuk A., Skwira A., Wróbel Z., and Wróbel Z., (2024) 3D-printed patient-specific implants made of polylactide (PLDLLA) and β-tricalcium phosphate (β-TCP) for corrective osteotomies of the distal radius, *3D Print. Med.*, vol. 10, p. 42, 2024. doi: 10.1186/s41205-024-00240-z.

[13] Jayawardane H., Davies I. J., Gamage J. R., John M., and Biswas W. K., (2023) Sustainability perspectives-A review of additive and subtractive manufacturing, *Sustain. Manuf. Serv. Econ.*, vol. 2, p. 100015, 2023. doi: 10.1016/j.smse.2023.100015.

[14] Jiménez A., Bidare P., Hassanin H., Tarlochan F., Dimov S., and Essa K., (2021) Powder-based laser hybrid additive manufacturing of metals: A review, *Int. J. Adv. Manuf. Technol.*, vol. 114, pp. 63-96, 2021. doi: 10.1007/s00170-021-06855-4.

[15] Joghan H. D., Hölker-Jäger R., Komodromos A., and Tekkaya A. E., (2023) Hybrid additive manufacturing of forming tools, *Automot. Innov.*, vol. 6, pp. 311-323, 2023. doi: 10.1007/s42154-023-00239-y.

[16] Jung S., Kara L. B., Nie Z., Simpson T. W., and Whitefoot K. S., (2023) Is additive manufacturing an environmentally and economically preferred alternative for mass production? *Environ. Sci. Technol.*, vol. 57, no. 17, pp. 6373-6386, 2023. doi: 10.1021/acs.est.2c04927.

[17] Kapil S., Rajput A. S., and Sarma R., (2022) Hybridization in wire arc additive manufacturing, *Front. Mech. Eng.*, vol. 8, p. 981846, 2022. doi: 10.3389/fmech.2022.981846.

[18] Karunakaran K. P., Suryakumar S., Pushpa V., and Akula S., (2010) Low cost integration of additive and subtractive processes for hybrid layered manufacturing, *Robot. Comput.-Integr. Manuf.*, vol. 26, pp. 490-499, 2010. doi: 10.1016/j.rcim.2010.03.008.

[19] Krimpenis A. A. and Iordanidis D. M., (2023) Design and analysis of a desktop multi-axis hybrid milling-filament extrusion CNC machine tool for non-metallic materials, *Machines*, vol. 11, no. 6, p. 637, 2023. doi: 10.3390/machines11060637.

[20] Lalegani D M., Serjouei A., Zolfagharian A., Fotouhi M., Moradi M., Ariffin M. K. A., and Bodaghi M., (2022) A review on additive/subtractive hybrid manufacturing of directed energy deposition (DED) process, *Adv. Powder Mater.*, vol. 1, no. 4, p. 100054, 2022. doi: 10.1016/j.apmate.2022.100054.

[21] Lauwers B., Klocke F., Klink A., Tekkaya A. E., Neugebauer R., and Mcintosh D., (2014) Hybrid processes in manufacturing, *CIRP Ann.-Manuf. Technol.*, vol. 63, no. 2, pp. 561-583, 2014. doi: 10.1016/j.cirp.2014.05.003.

[22] Liu R., Wang Z., Sparks T., Liou F., and Newkirk J., (2017) Aerospace applications of laser additive manufacturing, in *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications*, Cambridge, UK: Woodhead Publishing, 2017, pp. 351-371. doi: 10.1016/B978-0-08-100433-3.00013-0.

[23] Loyda A., Arizmendi M., Ruiz de Galarreta S., Rodriguez-Florez N., and Jimenez A., (2023) Meeting high precision requirements of additively manufactured components through hybrid manufacturing, *CIRP J. Manuf. Sci. Technol.*, vol. 40, pp. 199-212, 2023. doi: 10.1016/j.cirpj.2022.11.011.

[24] Marques A., Guimarães B., Bartolomeu F., Miranda G., Silva F. S., and Carvalho Ó., (2023) Multi-material Inconel 718-aluminium parts targeting aerospace applications: A suitable combination of low-weight and thermal properties, *Opt. Laser Technol.*, vol. 158, p. 108913, 2023. doi: 10.1016/j.optlastec.2022.108913.

[25] Mechete A., Tarlochan F., and Kucukvar M., (2023) A review of conventional versus additive manufacturing for metals: Life-cycle environmental and economic analysis, *Sustainability*, vol. 15, no. 16, p. 12299, 2023. doi: 10.3390/su151612299.

[26] Merklein M., Junker D., Schaub A., and Neubauer F., (2016) Hybrid additive manufacturing technologies-An analysis regarding potentials and applications, *Phys. Procedia*, vol. 83, pp. 549-559, 2016. doi: 10.1016/j.phpro.2016.08.057.

[27] Mertkan İ. A., Tezel T., and Kovan V., (2022) Surface and dimensional quality of thermoplastics manufactured by additive manufacturing-based hybrid manufacturing, *Res. Sq.*, preprint, 2022. doi: 10.21203/rs.3.rs-2229678/v1.

[28] Nagamatsu H., Sasahara H., Mitsutake Y., and Hamamoto T., (2020) Development of a cooperative system for wire and arc additive manufacturing and machining, *Addit. Manuf.*, vol. 31, p. 100896, 2020. doi: 10.1016/j.addma.2019.100896.

[29] Nau B., Roderburg A., and Klocke F., (2011) Ramp-up of hybrid manufacturing technologies, *CIRP J. Manuf. Sci. Technol.*, vol. 4, no. 3, pp. 313-316, 2011. doi: 10.1016/j.cirpj.2011.04.003.

[30] Pragana J. P. M., Sampaio R. F. V., Bragança I. M. F., Silva C. M. A., and Martins P. A. F., (2021) Hybrid metal additive manufacturing: A state-of-the-art review, *Adv. Ind. Manuf. Eng.*, vol. 2, p. 100032, 2021. doi: 10.1016/j.aime.2021.100032.

[31] Prasad G., Arunav H., Dwight S., Ghosh M. B., Jayadev A., and Nair D. I., (2024) Advancing sustainable practices in additive manufacturing: A comprehensive review on material waste recyclability, *Sustainability*, vol. 16, no. 23, p. 10246, 2024. doi: 10.3390/su162310246.

[32] Praveena B. A., Lokesh N., Buradi A., Santhosh N., Praveena B. L., and Vignesh R., (2022) A comprehensive review of emerging additive manufacturing (3D printing technology): Methods, materials, applications, challenges, trends and future potential, *Mater. Today Proc.*, vol. 52, pp. 1309-1313, 2022. doi: 10.1016/j.matpr.2021.11.059.

[33] Saxena K. K., Bellotti M., Qian J., Reynaerts D., Lauwers B., and Luo X., (2018) Chapter 2-Overview of Hybrid Machining Processes, in *Hybrid Machining*, London, UK: Academic Press, 2018, pp. 21-41. doi: 10.1016/B978-0-12-813059-9.00002-6.

[34] Schuh G., Kreysa J., and Orilski S., (2009) Roadmap 'Hybride Produktion', *Z. Wirtsch. Fabr.*, vol. 104, no. 5, pp. 385-391, 2009. doi: 10.3139/104.110072.

[35] Sebbe N. P. V., Fernandes F., Sousa V. F. C., and Silva F. J. G., (2022) Hybrid manufacturing processes used in the production of complex parts: A comprehensive review, *Metals*, vol. 12, no. 11, p. 1874, 2022. doi: 10.3390/met12111874.

[36] Soe A. N., Sombatmai A., Promoppatuma P., Srimaneepong V., Trachoo V., and Pandee P., (2024) Effect of post-processing treatments on surface roughness and mechanical properties of laser powder bed fusion of Ti-6Al-4V, *J. Mater. Res. Technol.*, vol. 32, pp. 3788-3803, 2024. doi: 10.1016/j.jmrt.2024.08.197.

[37] Sun G. F., Shen X. T., Wang Z. D., Zhan M. J., Yao S., Zhou R., and Ni Z. H., (2019) Laser metal deposition as repair technology for 316L stainless steel: Influence of feeding powder compositions on microstructure and mechanical properties, *Opt. Laser Technol.*, vol. 109, pp. 71-83, 2019. doi: 10.1016/j.optlastec.2018.07.051.

[38] Williams S. W., Martina F., Addison A. C., Ding J., Pardal G., and Colegrove P., (2016) Wire + Arc Additive Manufacturing, *Mater. Sci. Technol.*, vol. 32, no. 7, pp. 641-647, 2016. doi: 10.1179/1743284715Y.0000000073.

[39] Xu Z., Ouyang W., Jia S., Jiao J., Zhang M., and Zhang W., (2020) Cracks repairing by using laser additive and subtractive hybrid manufacturing technology, *J. Manuf. Sci. Eng.*, vol. 142, no. 3, p. 031006, 2020. doi: 10.1115/1.4046161.

[40] Yue W., Zhang Y., Zheng Z., and Lai Y., (2024) Hybrid laser additive manufacturing of metals: A review, *Coatings*, vol. 14, no. 3, p. 315, 2024. doi: 10.3390/coatings14030315.

[41] Zhu Z., Dhokia V. G., Nassehi A., and Newman S. T., (2013) A review of hybrid manufacturing processes-state of the art and future perspectives, *Int. J. Comput. Integr. Manuf.*, vol. 26, no. 7, pp. 596-615, 2013. doi: 10.1080/0951192X.2012.749530.