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MATERIAL CHARACTERIZATION OF METAL PARTS PRINTED WITH HIGHLY-FILLED POLYMERS FILAMENTS: A REVIEW

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Abstract. *Among different Additive Manufacturing (AM) technologies, Material Extrusion (MEX) is one of the most versatile and widely used, typically applied with polymers. Recently, increasing attention has been given to MEX of highly-filled polymers (HP) with metal powder, allowing low-cost conventional polymer 3D printers to fabricate parts of different kinds of metals with minor modifications. Studies have stated the benefits of metal MEX technology, but the process has some limitations, and understanding them is critical to designing a part manufactured by this procedure. After printing, post-processing steps are necessary to eliminate all traces of polymeric material, obtaining a final metallic part with 14-23% shrinkage of the total part volume, depending on printing orientation and material. The final parts' integrity is highly dependent on the filament deposition pathway, and residual stresses can distort or even crack the parts after sintering. Porosity and effects on mechanical properties are also consequences of the post-processing steps. Metal MEX parts' mechanical properties are usually lower when compared to Metal Injection molding (MIM) and other AM technologies, such as Selective Laser Melting (SLM). The present paper aims to review the printing process and the characterization of materials produced by metal MEX, the most common defects, and other particularities that have been researched over the last few years. This study contributes to the emerging field of metal MEX, highlighting the main characteristics of the final parts obtained with this process.*

Keywords: *Metallic 3D Printing, Material Characterization, Mechanical Properties, Metal Additive Manufacturing Process*

1. INTRODUCTION

Additive manufacturing (AM), commonly named Three-dimensional (3D) printing, has recently gained space in the industry; researchers worldwide are using it to discover new ways to solve problems due to its many benefits. It reduces cost by reducing material waste and fabrication time. In addition, it provides an increase in design flexibility and option, dealing with geometric and material complexities which cannot be obtained using traditional subtractive manufacturing processes (Hegab, 2016; Karayel and Bozkurt, 2020). AM is classified into different categories (or technologies), and each one differs from another in the manner of the application process, the initial state of the material, and the solidification principle (Mehrpouya *et al.*, 2021).

Among these different AM categories, material extrusion (MEX) is one of the most versatile and widely used due to its advantages over other methods: low-cost equipment, a great variety of materials, and easy operation. In this technology, the material is fed into a heated chamber where it melts, becoming a highly viscous fluid that is extruded through a nozzle and deposited on a build platform layer by layer, following a toolpath calculated by the printer control software and forming a three-dimensional object (Mazzanti *et al.*, 2019).

Amorphous polymers are the most used materials in MEX. However, over the last few years, increasing attention has been directed at MEX of highly-filled polymers (HP) with metal powder, proving that conventional polymer 3D printers, which are low-cost and readily available, can be successfully adapted to fabricate parts of different kinds of metals, such as stainless steel, titanium alloys, nickel alloys, cobalt, and aluminum alloys (Gonzalez-Gutierrez *et al.*, 2018; Bourell *et al.*, 2017; Barba *et al.*, 2020; Glerum *et al.*, 2020). The material used as feedstock is a polymer-metal blend used to print the green part, which is then submitted to post-processing stages to obtain the final metallic product (Miclette *et al.*, 2022; Suwanpreecha and Manonukul, 2022). As this AM technique implies using a filament containing several organic components, a debinding step is thus necessary, usually done in an atmosphere with controlled temperature and gaseous exposure, to eliminate all traces of organic material before final consolidation by sintering.

Studies have clearly stated the benefits of metal MEX technology as discussed before; however, there are still some limitations, such as anisotropy in microstructure and the effects of different build orientations on mechanical properties (Sun *et al.*, 2018; Lewandowski and Seifi, 2016). Metal MEX final parts can present imperfections and crack-like defects related to printing orientation and porosity after sintering, leading to low mechanical strengths. Also, metal MEX final parts can show imperfections and crack-like defects related to printing orientation and porosity after sintering, leading to low mechanical strengths (Bjørheim and Lopez, 2021; Galati and Minetola, 2019). Understanding these limitations is critical to designing a part manufactured by this procedure. Therefore, the present paper aims to review what has been studied about this manufacturing process and the characterization of materials produced by metal MEX over the last few years.

2. METHODS

This academic review was conducted through a comprehensive and critical bibliographic search across various databases, including Science Direct, Scopus, and Electronic Library Online (SciELO). This search focused on identifying articles published between 2017 and 2023. The following keywords were used as search basis: "Metallic 3D Printing," "Material Characterization," "Mechanical Properties," and "Metal Additive Manufacturing Process".

3. THE METAL MEX PROCESS

3.1 Material

The material used is a polymer-metal blend with metal powder, usually in a range of 3–50 µm, similar to conventional metal injection molding (MIM). Still, their chemical formulations differ by lower metallic powder concentration and higher elastomer contents at the HP. According to Suwanpreecha and Manonukul (2022), HP filaments vary between 50% and 90% of metal solid loading (in weight). Studies of the morphology of the metallic powder with Scanning Electron Microscopy (SEM) images show that most particles have a spherical shape, with a small proportion of the powder having an irregular shape, and its particle-size distribution is relatively uniform, as shown in Fig. 1 (Miclette *et al.*, 2022; Suwanpreecha and Manonukul, 2022; Xu *et al.*, 2023).
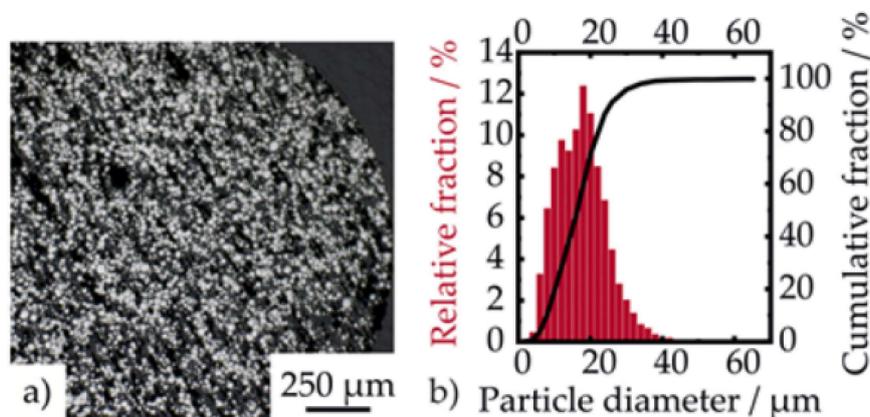

Figure 1. Microscopy Image of a filament cross-section with the embedded 316 L particles (a) and the powder's particle size distribution (b). Source: Thompson *et al.* (2019).

Among all the high-filled filaments available, 316L stainless steel and 17-4PH are two of the most common materials used in a wide range of areas, such as marine environments, chemical engineering, and nuclear power generation, due to their mechanical properties. It has significant tensile and impact strength and corrosion resistance at operating temperatures below 300 °C (Xu *et al.*, 2023; Ponnusamy *et al.*, 2021; Abe *et al.*, 2021).

3.2 Printing

This polymer-metal blend undergoes heating until the filament reaches a softened state, enabling it to be extruded through a printing nozzle. Subsequently, the extruded material is deposited onto a heated printing bed, promoting enhanced adhesion between the printed components and the building platform. This meticulous layer-by-layer deposition process follows the pre-established digital model, creating a fully formed three-dimensional object (Nurhudan *et al.*, 2021).

The Metal MEX technique can be categorized into three distinct types, determined by the specific feeding system employed in the printer. The first type is screw-based, where the feedstock is propelled forward using a rotating screw mechanism. The second type is plunger-based, which utilizes a plunger to apply pressure and control the extrusion of

the material. Lastly, the filament-based type relies on a feed system to deliver the material consistently to the printing nozzle (Fig. 2). This flexibility in feeding systems allows for customization and optimization based on the specific requirements of the printing project. Each type presents advantages and considerations, offering diverse options for achieving desired outcomes in Metal MEX printing (Gonzalez-Gutierrez *et al.*, 2018; Suwanpreecha and Manonukul, 2022). The filament-based type is the most common, and it is the one focused on in this review, given that conventional polymer 3D printers, which are low-cost and readily available, can be successfully adapted to fabricate these green metallic parts (Gonzalez-Gutierrez *et al.*, 2018; Barba *et al.*, 2020; Glerum *et al.*, 2020).
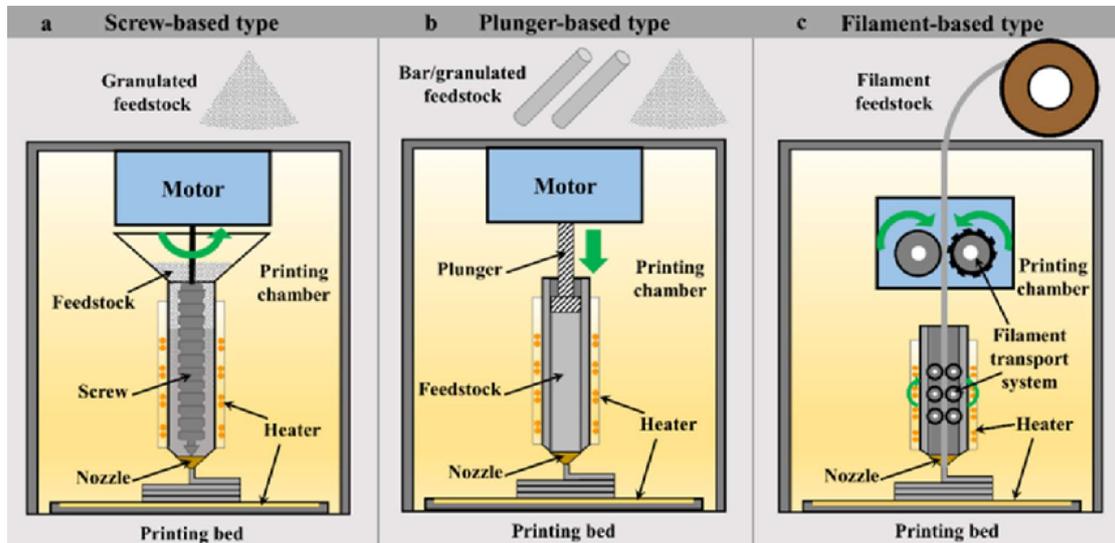

Figure 2. Types of material extrusion additive manufacturing are classified by feeding system: screw-based (a), plunger-based (b), and filament-based (c) types. Source: Suwanpreecha and Manonukul (2022).

4.2 Debinding

The debinding process involves eliminating the organic binder from a printed part using thermal, solvent, or catalytic methods. The choice of method depends on the composition and constituents of the binder. Thermal debinding entails applying heat to degrade, evaporate, or extract the binder through liquid extraction. The temperatures can range from 60°C to 600°C, incorporating specific dwell times at selected temperatures to facilitate the thermal decomposition of the binder constituents. It is crucial to avoid excessively high temperatures during the process, as they can trigger the decomposition of the material into carbonaceous compounds (Nurhudan *et al.*, 2021; Spiller *et al.*, 2022).

In the catalytic debinding process, a catalytic agent, such as nitric or oxalic acid, removes the binder from the material. This process involves subjecting the material to temperatures ranging from 110°C to 150°C in the presence of the catalytic agent. This catalytic agent interacts with the binder, causing it to degrade and release from the material more rapidly than other debinding methods (Nurhudan *et al.*, 2021).

However, to reduce the relatively long debinding time associated with thermal debinding, solvents like heptane or trichloroethane can dissolve the soluble binder, such as wax, in a wax-polyethylene-polypropylene-based binder. Water can serve as a solvent for certain water-soluble feedstocks based on glycol and polyvinyl alcohol. In contrast, binders with gelation properties, like those using polysaccharides plus water, rely on air drying to remove water.

The amount of removed polymer binder can be evaluated by measuring the weight loss after different debinding times. The process can be considered completed when the weight percentage of extracted polymer reaches 99% of the total amount added (Thompson *et al.*, 2019).

In all debinding methods, a skeleton or residual binder structure remains to provide sufficient strength and shape retention until the onset of sintering. This residual backbone is thermally removed through pre-sintering at temperatures between 200°C and 600°C.

4.3 Sintering

Once the organic binder has been eliminated, the fabricated specimens undergo a sintering process. In the case of stainless steel powder, the sintering cycle typically involves subjecting the samples to temperatures as high as 1360°C or even higher for an extended period, which is also influenced by the particle size of the powder used. To ensure the parts' mechanical integrity and microstructural purity, sintering is typically conducted under controlled atmospheres such as inert gas or reducing gas, preventing the formation of oxides and their detrimental effects (Spiller *et al.*, 2022).

Residual porosity presents a challenge in producing Metal MEX parts, which is also strongly influenced by the sintering process. It can originate from both the printing phase and the post-processing stage, it arises from insufficient

densification during sintering. Increasing sintering temperatures or prolonging the sintering time can help reduce porosity, although this can result in an undesired consequence: the enlargement of grain size. However, it is possible to promote effective sintering by using metal powder with smaller average dimensions and regular shapes, as this facilitates densification and reduces the occurrence of pores (Spiller *et al.*, 2022).

The sintering process causes shrinkage from 14% to 23% of the total volume, depending on printing orientation and material, which needs to be carefully compensated on the CAD model to acquire the required dimension (Wickramasinghe *et al.*, 2020; Coffigniez *et al.*, 2021).

4. MATERIAL CHARACTERIZATION

4.1 Filament characterization

The characteristics such as shape, size, surface morphology, and volume fraction of metallic particles directly impact the processing properties during fused filament fabrication and sintering. Consequently, these factors significantly affect the overall quality of the final metallic implant (Gloeckle *et al.*, 2020).

Existing studies demonstrate a correlation between an increase in the average particle size and a decrease in the apparent shear viscosity of the feedstock, as well as the secant modulus and elongation at the break of filaments. This observed change in properties is significant because it implies that filaments containing smaller particles are more suitable for the printing process. In comparison, materials with larger particles exhibit limitations and challenges in achieving successful prints (Kukla *et al.*, 2017).

Studies show that reducing particle sizes offers significant benefits regarding the material extrusion and sintering processes. By decreasing the size of the particles, the surface area increases, leading to enhanced contact and interaction between the particles. This, in turn, facilitates more efficient sintering and densification. Another advantage of smaller particle sizes is the reduction in diffusion distance during the sintering process. With finer particles, the paths that atoms or molecules must traverse to reach their destination are shorter. This decreased diffusion distance allows for faster and more effective particle bonding, resulting in higher sintering densities (Moghadasi *et al.*, 2020; Miyanaji *et al.*, 2019).

4.2 Characterization of printed parts

Several researchers use SEM images to evaluate the relative densities of printed parts (Abe *et al.*, 2021). It is important to emphasize that the impact of the printing trajectory on the formation of samples in additive manufacturing is of utmost importance. Scientific studies indicate that a significant level of porosity adversely affects the mechanical properties of printed objects, resulting in diminished tensile strength, modulus of elasticity, and relative density. In the study of Xu et al. (2023), it was demonstrated that employing a cross-printing technique (one layer printed with 27° and the next with a 152° angle) promotes an effective reduction of voids between layers, increasing the density of final parts (Fig. 3). According to the authors, applying a rotation between layers makes the deposited filaments to fill some of the gaps formed on a previous layer.
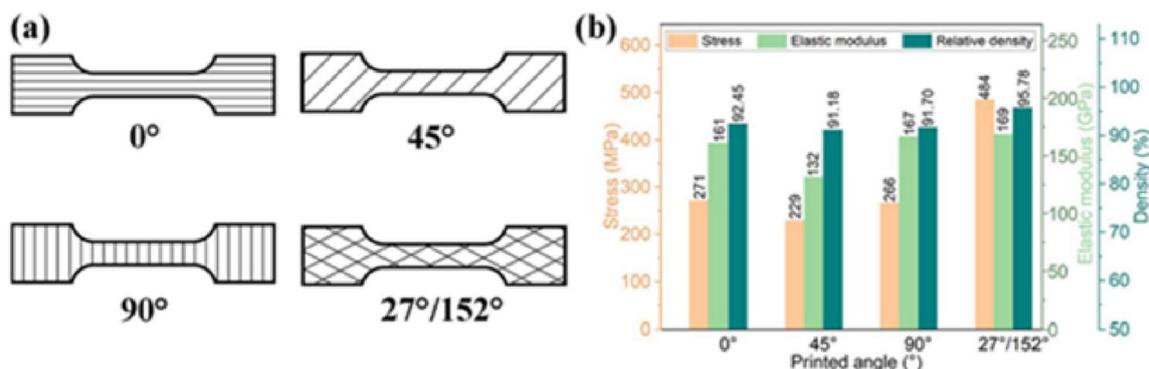

Figure 3. Print angle schematic image (a) and mechanical properties and relative density of sintered samples printed at different angles (b). (Adapted from Xu et al., 2023).

The mechanical properties of printed parts are determined through mechanical tests. However, parts in both heat-treated and non-heat-treated, manufactured by metal MEX, have an anisotropic behavior, in which the specimen printed with its layer direction perpendicular to the tensile direction delivers the highest strength (Abe *et al.*, 2021).

Comparing different AM methods is essential to assess the manufacturing quality of a product. This comparison identifies differences in manufacturing processes, their advantages, and limitations. It also allows for evaluating process efficiency and associated costs. Some methods may be more efficient regarding production time, resource consumption, material waste, and ease of operation. However, they may present lower quality in manufactured parts, which must also

be considered. Tables 1, 2, and 3 demonstrate the highest strength achieved with metal MEX compared to the most common metal AM methods (SLS and SLM) of two of the most common materials used, as discussed before.

Table 1. Experimental results for mechanical properties of different materials printed by metal MEX

Mechanical properties	Stainless steel (17-4PH)	Stainless steel (316L)
Yield Strength (MPa)	800	194 ± 19
Tensile Strength (MPa)	1050	441 ± 27
Elongation at Break (%)	5	29,5 ± 3,8
Hardness (HV)	285	145,2 ± 6,7
Porosity (%)	4,3	8
Shrinkage (%)	Length:20.3 Width:15.9 Height:15.2	Width:16,3 Height:17,4
References	Gonzalez-Gutierrez *et al.* (2019)	Thompson *et al.* (2019)

Table 2. Experimental results for mechanical properties of different materials printed by selective laser melting (SLM)

Mechanical properties	Stainless steel (17-4PH)	Stainless steel (316L)
Yield Strength (MPa)	652,5	365 ± 22
Tensile Strength (MPa)	1104,73	563 ± 6
Elongation at Break (%)	20	46.7
Hardness (HV)	-	-
Porosity (%)	~0	~0
References	Ponnusamy *et al.* (2021)	Röttger *et al.* (2020)

Table 3. Experimental results for mechanical properties of different materials printed by selective laser sintering (SLS)

Mechanical properties	Stainless steel (17-4PH)	Stainless steel (316L)
Yield Strength (MPa)	620	520 ± 20
Tensile Strength (MPa)	1100	660 ± 20
Elongation at Break (%)	16	39 ± 5
Hardness (HV)	-	-
Porosity (%)	~0	~0
References	Nurhudan *et al.* (2021)	Nurhudan *et al.* (2021)

As previously described, the advantages of Metal MEX include the potential for cheaper equipment, low production costs, mechanical simplicity, and ease of operation (Karayel and Bozkurt, 2020; Mohd Pu'ad *et al.*, 2020). However, the characterization of printed parts reveals the limitations of this technique. Researchers attribute the poor mechanical properties to defects such as high porosity compared to the other manufacturing processes (Pazhamannil *et al.*, 2021; Maleki *et al.*, 2021), as demonstrated in Tables 1, 2, and 3. Another factor contributing to this situation is the layer thickness. A higher layer thickness can reduce the strength of the final part, which is influenced by the material type and nozzle size (Dev and Srivastava, 2020). Increasing powder grain size can also decrease the printed part's strength (Thompson *et al.*, 2019). Given this situation, there is an opportunity to develop this technique based on process parameters to optimize the mechanical properties and make them more reliable.

5. CONCLUSIONS

Metal MEX has emerged as an up-and-coming and successful manufacturing alternative for producing components using highly filled polymers containing dispersed metal powder. The outcomes of the printing process have yielded satisfactory results. Although, it is evident from mechanical tests that further advancements are necessary for the fabrication process to attain components with mechanical properties comparable to those of most common additive manufacturing methods.

Among the primary challenges encountered, porosity is a critical concern that demands focused attention. Therefore, a concerted effort must be directed toward enhancing the density of the specimens. This pursuit for improved density encompasses the advanced additive manufacturing techniques employed during printing and subsequent post-

processing procedures. Acknowledging the influential role played by these stages is imperative, as they contribute significantly to forming pores within the parts.

The literature shows better mechanical properties can be achieved with a cross-printing technique (rotating angle between layers), high sintering temperatures, long sintering time, and using metal powder with smaller average dimensions and regular shapes. However, additional investigations are warranted to gain a more comprehensive understanding of the material's characteristics and further explore the technique's potential. These endeavors should encompass in-depth material characterization studies to elucidate the underlying mechanisms responsible for the observed mechanical behavior. Furthermore, an extensive exploration of the technique's capabilities will enable the identification of novel strategies and optimizations that can maximize the performance and viability of Metal MEX in diverse applications.

6. ACKNOWLEDGEMENTS

7. REFERENCES

Abe, Y., Kurose, T., Santos, M. V. A., Kanaya, Y., Ishigami, A., Tanaka, S. and Ito, H., 2021. "Effect of layer directions on internal structures and tensile properties of 17-4PH stainless steel parts fabricated by fused deposition of metals". *Materials*, Vol. 14, p.243.

Barba, D., Alabort, C., Tang, Y. T., Viscasillas, M. J., Reed, R. C. and Alabort, E., 2020. "On the size and orientation effect in additive manufactured Ti-6Al-4V". *Materials & Design*, Vol. 186, p. 108235.

Bjørheim, F. and Lopez, I. M. La Torraca, 2021. "Tension testing of additively manufactured specimens of 17-4 PH processed by Bound Metal Deposition". In *IOP Conference Series: Materials Science and Engineering*. IOP, Vol. 1201 p. 012037.

Bourell, D., Kruth, J. P., Leu, M., Levy, G., Rosen, D., Beese, A. M., and Clare, A., 2017. "Materials for additive manufacturing". *CIRP Annals*, Vol. 66, pp. 659-681.

Coffigniez, M., Gremillard, L., Perez, M., Simon, S., Rogollet, C., Bonjour, E., Jame, P. and Boulnat, X., 2021. "Modeling of interstitials diffusion during debinding/sintering of 3D printed metallic filaments: application to titanium alloy and its embrittlement". *Acta Materialia*, Vol. 219, p. 117224.

Dev, S. and Srivastava, R., 2020. "Experimental investigation and optimization of FDM process parameters for material and mechanical strength". *Materials Today: Proceedings*, Vol. 26, pp. 1995-1999.

Galati, M. and Minetola, P., 2019. "Analysis of density, roughness, and accuracy of the atomic diffusion additive manufacturing (ADAM) process for metal parts". *Materials*, Vol. 12, p. 4122.

Glerum, J. a., Kenel, C., Sun, T. and Dunand, D. C., 2020. "Synthesis of precipitation-strengthened Al-Sc, Al-Zr and Al-Sc-Zr alloys via selective laser melting of elemental powder blends". *Additive Manufacturing*, Vol. 36, p. 101461.

Gloeckle, C., Konkol, T., Jacobs, O., Limberg, W., Ebel, T. and Handge, U.A., 2020. "Processing of highly filled polymer–metal feedstocks for fused filament fabrication and the production of metallic implants". *Materials*, Vol. 13, p. 4413.

Gonzalez-Gutierrez, J., Cano, S., Schuschnigg, S., Kukla, C., Sapkota, J. and Holzer, C., 2018. "Additive manufacturing of metallic and ceramic components by the material extrusion of highly-filled polymers: a review and future perspectives". *Materials*, Vol. 11, p. 840.

Gonzalez-Gutierrez, J., Arbeiter, F., Schlauf, T., Kukla, C. and Holzer, C., 2019. "Tensile properties of sintered 17-4PH stainless steel fabricated by material extrusion additive manufacturing". *Materials Letters*, Vol. 248, pp. 165–168.

Hegab, H. A., 2016. "Design for additive manufacturing of composite materials and potential alloys: a review". *Manufacturing Rev.*, Vol. 3, p. 11.

Karayel, E. and Bozkurt, Y., 2020. "Additive manufacturing method and different welding applications". *Journal of Materials Research and Technology*, Vol. 9, pp. 11424-11438.

Kukla, C., Gonzalez-Gutierrez, J., Duretek, I., Schuschnigg, S. and Holzer, C., 2017. "Effect of particle size on the properties of highly-filled polymers for fused filament fabrication". In *AIP Conference Proceedings*. AIP Publishing LLC, Vol. 1914, p. 190006.

Lewandowski, J. J. and Seifi, M., 2016. "Metal additive manufacturing: a review of mechanical properties". *Annual Review of Materials Research*, Vol. 46, pp. 151-186.

Maleki, E., Bagherifard, S., Bandini, M. and Guagliano, M., 2021. "Surface post-treatments for metal additive manufacturing: Progress, challenges, and opportunities". *Additive Manufacturing*, Vol. 37, p. 101619.

Mazzanti, V., Malagutti, L. and Mollica, F., 2019. "FDM 3D printing of polymers containing natural fillers: A review of their mechanical properties". *Polymers*, Vol. 11, p. 1094.

Mehrpouya, M., Vosooghnia, A., Dehghanghadikolaei, A. and Fotovvati, B., 2021. "The benefits of additive manufacturing for sustainable design and production". In: *Sustainable Manufacturing*. Elsevier. Pp. 29-59.

Miclette, O., Côté, R., Demers, V. and Brailovski, V., 2022. "Material extrusion additive manufacturing of low-viscosity metallic feedstocks: performances of the plunger-based approach". *Additive Manufacturing*, Vol. 60, p. 103252.

Miyanaji, H., Momenzadeh, N. and Yang, L., 2019. "Effect of powder characteristics on parts fabricated via binder jetting process". *Rapid Prototyping Journal*, Vol. 25, pp. 332-342.

Moghadasi, M. W., Du, M., Li, Z., Pei, Z. and Ma, C., 2020. "Ceramic binder jetting additive manufacturing: effects of particle size on feedstock powder and final part properties". *Ceramics International*, Vol. 46, pp. 16966–16972.

Mohd Pu'ad, N. A. S., Abdul Haq, R. H., Mohd Noh, H., Abdullah, H. Z., Idris, M. I. and Lee, T. C., 2020. "Review on the fabrication of fused deposition modelling (FDM) composite filament for biomedical applications". *Materials Today: Proceedings*, Vol. 29, pp. 228-232.

Nurhudan, A. I., Supriadi, S., Whulanza, Y. and Saragih, A. S., 2021. "Additive manufacturing of metallic based on extrusion process: a review". *Journal of Manufacturing Processes*, Vol. 66, pp. 228-237.

Pazhamannil, R. V., Govindan, P. and Sooraj, P., 2021. "Prediction of the tensile strength of polylactic acid fused deposition models using artificial neural network technique". *Materials Today: Proceedings*, Vol. 46, pp. 9187-9193.

Ponnusamy, P., Sharma, B., Masood, S. H., Rahman Rashid, R. A., Rashid, R., Palanisamy, S. and Ruan, D., 2021. "A study of tensile behavior of SLM processed 17-4 PH stainless steel". *Materials Today: Proceedings*, Vol. 45, pp. 4531-4534.

Röttger, A., Boes, J., Theisen, W., Thiele, M., Esen, C., Edelmann, A. and Hellmann, R., 2020. "Microstructure and mechanical properties of 316L austenitic stainless steel processed by different SLM devices". *The International Journal of Advanced Manufacturing Technology*, Vol. 108, pp. 769-783.

Spiller, S., Kolstad, S. O. and Razavi, S. M. J., 2022. "Fabrication and characterization of 316L stainless steel components printed with material extrusion additive manufacturing". *Procedia Structural Integrity*, Vol. 42, pp. 1239-1248.

Sun, B., Lin, J. and Fu, M. W., 2018. "Dependence of processing window and microstructural evolution on initial material state in direct electric resistance heat treatment of NiTi alloy". *Materials & Design*, Vol. 139, pp. 549-564.

Suwanpreecha, C. and Manonukul, A., 2022. "A review on material extrusion additive manufacturing of metal and how it compares with metal injection moulding". *Metals*, Vol. 12, p. 429.

Thompson, Y., Gonzalez-Gutierrez, J., Kukla, C. and Felfer, P., 2019. "Fused filament fabrication, debinding and sintering as a low cost additive manufacturing method of 316L stainless steel". *Additive Manufacturing*, Vol. 30, p. 100861.

Wickramasinghe, S., Do, T. and Tran, P., 2020. "FDM-based 3D printing of polymer and associated composite: a review on mechanical properties, defects and treatments". *Polymers*, Vol. 12, p. 1529.

Xu, T., Long, F., Liang, Y., Zhang, H., Shi, S., Cheng, Y., Xu, G., Li, Z. and Ge, Y., 2023. "3D extrusion printing of 304 stainless steel/polypropylene composites and sintering process optimization". *Applied Physics A*, Vol. 129, p. 285.

8. RESPONSIBILITY NOTICE

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