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COMPARING METAL FILAMENTS AND PELLETS FOR MATERIAL EXTRUSION IN ADDITIVE MANUFACTURING: A REVIEW.

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Abstract. *Additive Manufacturing (AM) has become popular for producing precise and intricate metallic parts. However, customizing and optimizing the printing process can be challenging and expensive. Material Extrusion (ME) offers a more affordable and straightforward alternative for creating metal parts. Metal filaments, commonly used in ME, allow for parameter adjustment and desired outcomes but have limitations in metal/binder ratio flexibility and unconventional alloys. This study is a review that compares metal filament printing using traditional 3D printer heads and metal Pellets Additive Manufacturing (PAM) with a modified 3D printer. The comparison covers material preparation, printing parameters, characterization, and other factors. Evaluating these aspects provides insights into the benefits and drawbacks of using filaments or pellets for metal MEX, aiding in optimizing the process and exploring innovative feedstocks for additive manufacturing. The study also highlights the feasibility of using an in-house built extruder as a cost-effective alternative to commercial machines and filaments.*

Keywords: *additive manufacturing, material extrusion, metal filament, metal pellets, direct pellet extrusion.*

1. INTRODUCTION

According to the additive manufacturing (AM) standard terminology, known also as 3D printing, AM is a process of joining materials to make parts from 3D model data, usually layer by layer (ISO/ASTM, 2021). This approach differs from traditional manufacturing, which relies on cutting, drilling, and grinding away unwanted excess from a solid piece of material such as metal (Wong, 2012). This technology was developed by Charles Hull in 1986 in the form of stereolithography (SLA) technique, which used ultraviolet (UV) light to cure high-molecular weight polymers and stack them layer by layer. Nowadays researchers follow his steps to develop a number of latest techniques and materials for this desired use. In the same year, he founded the world's first 3D printing company, 3D Systems. After more than 30 years of development, the 3D printing technique is rapidly spreading owing to its advantages of material saving, high production efficiency, and low cost in different kinds of technologies. Currently, according to standard terminology for additive manufacturing, the 3D printing technologies are classified in seven categories, known as VAT photopolymerisation, material jetting (MJ), binder jetting (BJ), material extrusion (ME), powder bed fusion (PBF), sheet lamination (SL) and directed energy deposition (DED) (MONZÓN, 2015) and these technologies have been widely used in various fields including industrial design, sculpture, clothing, automotive, construction, and aerospace (Zhang, 2021). Additive manufacturing materials and methods enhance 3D printing technology as the advancements occur day by day and make it better for industrial use. Recent developments on these technologies helps to reduce the costs of 3D printers resulting in affordable processes which are capable of printing even customized products which is a challenge for manufacturers due to its high cost and complexity. Just because it is easy for AM technologies to print small quantities of customized products at affordable prices. The advancements on the processes improve its accuracy and versatility which helps to achieve a shift in the industries from 'Rapid proto-typing' to 'Rapid manufacturing' which means a complete part can be manufactured with the help of a rapid prototyping device. As the advancement occurs in the area of additive manufacturing various materials also are developed for 3D printing. These include materials like metals, polymers, composites, ceramics, wood, powder, glass and building materials, biodegradable materials, smart materials etc (Bhatia, 2023).

This review primarily centers around the utilization of material extrusion additive manufacturing (MEAM) for the production of metallic components, comparing filaments and pellets as raw material with particular emphasis on the utilization of pellets. Furthermore, it explores the prevalent types of machines employed for metal extrusion, namely plunger-based machines, screw-based machines, and filament-based machines. Additionally, it delves into the multi-step treatment of post processing, which involves the removal of a sacrificial polymeric binder material that shapes metallic powder particles.

2. TYPES OF MATERIAL EXTRUDERS BASED ON FEEDING FORMS

The pivotal component in 3D printers is the extruder, which assumes a critical role in ensuring efficient operation. An extruder can be defined as a device that employs heat to liquefy the feed material, subsequently extruding it through a nozzle while adhering to a predetermined path on the print bed (Shaik et al., 2021). In light of the specific focus of this paper on Material Extrusion Additive Manufacturing of Metal (Metal MEX), the primary objective of this study will revolve around exploring the various types of extruders that exhibit the capability of metal MEX.

2.1 Filament-based extruder

In filament extrusion, the fabrication process involves the use of a hot head extrusion system, where plastic filament is unwound and fed into the nozzle at a controlled rate. Once inside the nozzle, the filament melts upon reaching the glass transition temperature, facilitated by the heater in the hot end. It is essential that the filament is thermoplastic in nature for successful melting and subsequent fabrication. As the melted filament emerges from the nozzle, it quickly solidifies under ambient room temperature, resulting in the formation of a solid structure (Shaik et al., 2021).

Figure 1 illustrates the key components commonly found in a filament-based extruder. The teflon liner or filament guide serves the purpose of guiding the filament from the heat break into the nozzle, facilitating easier printing of PLA. However, it has temperature limitations compared to all-metal hot ends, which use a metal heat break instead of a Teflon guide. The heat sink, typically made of aluminum, features fins on its outer surface to dissipate heat from the heat block and prevent filament preheating, which could lead to overflow or line clogging as the material can cool and solidify inside the heat break. Cooling fans play a crucial role in enhancing print quality by promoting consistent cooling and solidification of the printed object, reducing dependency on ambient temperature and improving bridging capabilities. The heat break, often constructed from titanium or stainless steel, acts as a poor conductor of heat and aims to minimize the time the filament spends in a molten state to prevent overflow or clogging. It serves as the connection between the heat sink and heat block. The heat block, commonly composed of aluminum, connects the nozzle to the heat break and houses the heater cartridge and thermistor, which detects the temperature of the heat block. For high-temperature printing, a thermocouple might be used instead. The nozzle guides the molten filament and deposits it onto the build platform in a continuous flow of material (Shaik et al., 2021).

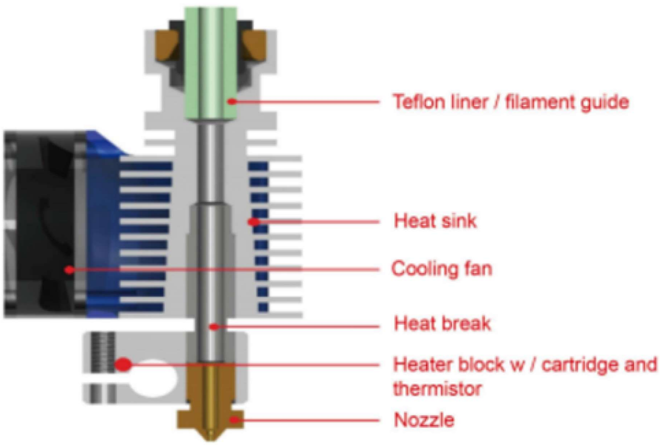

Figure 1. Cross section of a filament-based extruder (Shaik et al., 2021).

The advantages of the filament-based process are safety, simplicity and familiarity of the process, and it uses low-cost equipment as the general desktop polymer 3D printers can be used with the metal MEX filament. The high-volume fraction of metal in the filament results in a high wear rate of the printing nozzle, hence, a special ruby or hardened steel nozzle should be installed to produce a stable flow of the filament, prolong the nozzle life (Chen and Thomson, 2010) and reduce contamination. The main disadvantage of this process is the need for filament production, which requires single/twin screws or plunger extrusion equipment for filament fabrication (Thompson, 2019), plus special know-how, e.g., the selection of appropriate binder types, suitable mixing procedure and the filament fabrication technique (Agarwala et al., 1996).

2.2 Plunger-based extruder

The plunger-based Material Extrusion (MEX) method employs either bar or granulated feedstock, which is introduced into the nozzle of the plunger system, which is illustrated in Figure 2. One notable advantage of this system is its superior material handling capability, which is notably simpler compared to filament feedstock. Additionally, the solid loading capacity of bar feedstock can be higher than that of filament-based printers, making it comparable to feedstock used in Metal Injection Molding (MIM) processes. However, a key drawback of the plunger-based system, in contrast to the screw-based system, is the additional step involved in preparing the bar feedstock. The bar feedstock can be prepared by extruding a mixture of metal powder and polymer binders, which is subsequently cut to the desired size for feeding into the plunger-based extruder. (Suwanpreecha and Manonukul, 2022). Furthermore, in the plunger-based MEX system, print discontinuity can occur when the feedstock needs to be replenished. This pause in printing can result in visible seams or discontinuities in the printed object, affecting its overall quality and aesthetics. (Giberti et al., 2016).

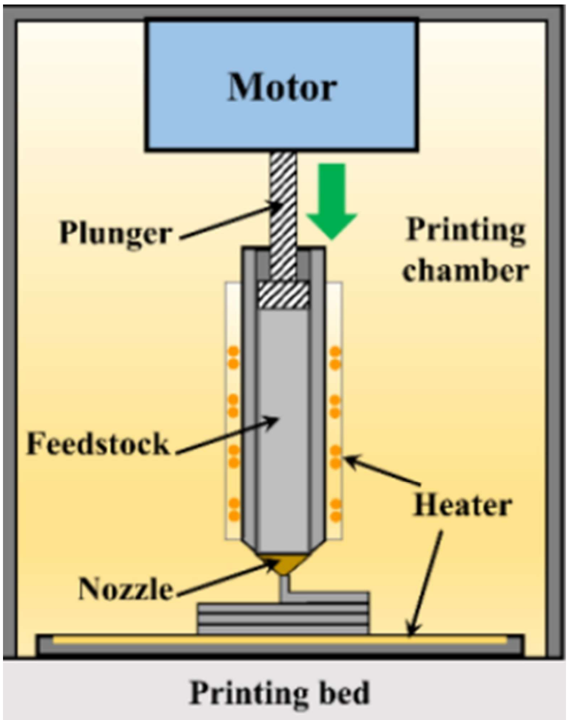

Figure 2. Cross section of a plunger-based extruder (Shaik et al., 2021).

2.3 Screw-based extruder

The availability of high-quality metal filament and bar feedstocks remains limited in terms of alloy selection. As a result, the screw-based extruder currently stands as the most versatile option regarding material choices. In the screw-based MEX approach, granulated feedstock is utilized in a similar manner to MIM. The feedstock is transported within the system through the rotation of a screw mechanism while being simultaneously heated by heating elements to a temperature surpassing the glass transition temperature of the polymer binder (Valkenaers et al., 2013). This process is illustrated in Figure 3, demonstrating the feedstock transportation and heating within the screw-based MEX system.

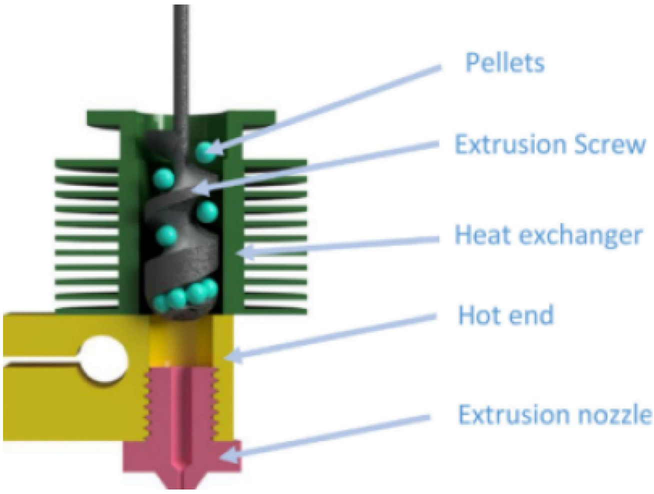

Figure 3. Schematic view of the screw-based extruder (Martin et al., 2022).

The shape of the extrusion screw and its enclosure is optimized to enhance material conveying and flow control in the extrusion process (Hinrichs and Lilleleht, 1970). The extrusion screw is typically divided into three sections: the feeding zone, transition zone, and metering zone, as depicted in Figure 4. The screw profile undergoes a reduction in available volume in the transition section, leading to increased pressure. This design facilitates the crushing of pellets and expulsion of air bubbles, resulting in a homogeneous material flow at the extrusion head outlet. Additionally, the entry part of the screw casing incorporates helicoidal stripes to enhance the friction factor and improve the conveying of the pellets (Martin et al., 2022).

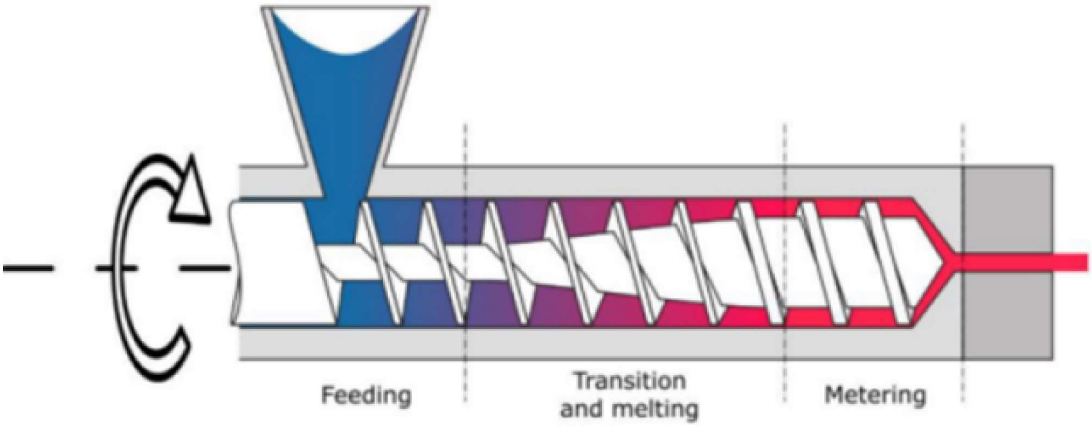

Figure 4. Typical design of the zones of a screw-based extruder (Martin et al., 2022).

The continuous screw-based MEX process offers several advantages over plunger- and filament-based methods. It enables high productivity through a continuous filling system, eliminating the need for additional processing steps in bar or filament preparation. It allows for the utilization of high solid loading, equivalent to that of MIM. The continuous feedstock filling system ensures uninterrupted printing, reducing printing time by eliminating the need for stoppages during feedstock replenishment and re-heating. Additionally, it eliminates the requirement for specialized equipment and expertise in handling brittle and challenging filament feedstock. However, careful control of the size of granulated feedstock (<5 mm) is necessary to maintain stability during printing and minimize defects caused by air entrapment (Bellini, 2005).

The size of the granulated feedstock in screw-based MEX systems is a critical factor to consider. If the granules are too large, they may not soften uniformly and adequately in the feeding system, affecting the quality of the printed parts. On the other hand, if the granules are too small, they may lead to blockages in the hopper, impeding the smooth flow of feedstock. One advantage of the screw-based MEX process is the ability to easily recycle printed mono-material green parts with defects or errors. These parts can be crushed and sieved before being reintroduced into the printer hopper, similar to the re-use of MIM injected parts with defects and runner systems (Manonukul et al., 2007).

Achieving stable and consistent flow rate of the material remains a challenge in the screw-based MEX system, affecting the fabrication of 3D parts. The presence of trapped air within the softened material can lead to variations in flow rate and compromise print quality. Additionally, the high viscosity of the feedstock requires a printing system with sufficient strength and stability to handle the extrusion process effectively. This is necessary to ensure precise control over the material flow and minimize potential issues such as clogging or uneven extrusion. Overcoming these challenges is crucial for obtaining reliable and high-quality 3D printed parts using the screw-based MEX process (Suwanpreecha and Manonukul, 2022).

2.4 Hybrid extruders

To address the limitations and leverage the benefits of different extruder types there is the option of combining two or more extruders. By integrating multiple extruders into a single system, it becomes possible to leverage their unique capabilities and functionalities (Netto et al., 2021).

To provide a few notable examples, as illustrated in Figure 5, Reddy et al. (2007) devised an extruder that mitigates the drawbacks associated with a single screw extruder by integrating two screw-based extruders. However, due to its substantial weight, the extruder necessitates a fixed position while the print bed moves. Similarly, Annoni (2016) developed an extruder capable of generating high levels of extrusion pressure by combining a screw-based and a plunger-based extruder. Nevertheless, it encounters the same weight-related challenge as the Reddy et al. extruder. In contrast to the aforementioned screw-assisted printheads, which integrate both the processing and deposition units into a single assembly, Khondoker and Sameoto (2019) propose an alternative design. Their approach combines a screw-based feeder with a filament-based deposition head, effectively decoupling the inherent limitations imposed by the weight and inertia of the screw extruder from the speed and resolution requirements of the deposition head.

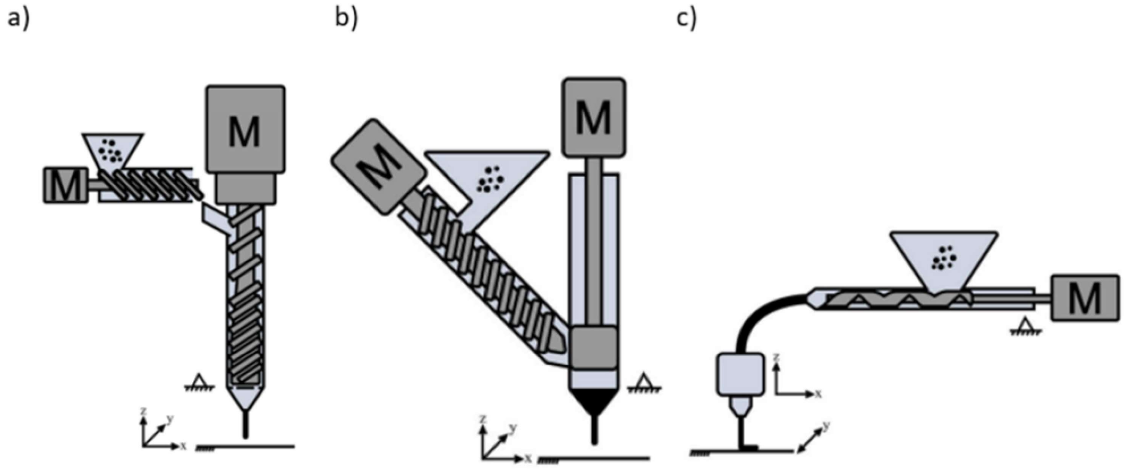

Figure 5. A few examples of hybrid extruders developed by a) Reddy et al., b) Annoni and c) Khondoker and Sameoto (Netto et al., 2021).

3. MULTI-STEP TREATMENT PROCESS

In the additive manufacturing process for functional parts, printing is the first step, where granulates are transformed into a "green" part composed of a target material in the form of powders encapsulated in a polymer matrix (Martin, 2022). Optimizing printing parameters, such as printing and bed temperature, number of perimeters, infill pattern and density, printing speed, flow rate multiplier, and layer thickness, is crucial for achieving desired properties (Suwanpreecha, 2022). Printing speed and flow rate multiplier, in particular, significantly impact the quality of the green parts and should be carefully adjusted (Singh, 2021). For metal MEX, which has higher viscosity compared to general polymers, a lower printing speed is recommended (Shaikh, 2021). The cooling system also plays a critical role in the metal MEX printing process (Thompson, 2019). These factors collectively influence the quality and characteristics of the green part, setting the foundation for subsequent stages in the additive manufacturing process.

In the second step, chemical debinding takes place to remove a portion of the polymer binder, resulting in a "brown" part. This process aims to dissolve part of the polymer matrix to create a network of open pores, facilitating the evacuation of the remaining polymer as gas during the next stage (Martin, 2022). In the case of conventional multiple-component binders, the debinding process consists of two steps: primary debinding and secondary debinding. The primary debinding step focuses on removing the plasticizer component, which is a low molecular weight polymer. This step creates interconnected pore paths within the material. Subsequently, in the secondary debinding step, the backbone component of the binder, which is a high molecular weight polymer, is removed. The primary debinding process can be further categorized into three types based on the type of polymer used as the main binder: solvent debinding, catalytic debinding, and water debinding. Solvent debinding is employed to remove wax-based binders, catalytic debinding is used to remove POM-based binders (such as Ultrafuse® filament), and water debinding is suitable for removing water-soluble binders like polyethylene glycol. The choice of debinding method depends on the specific binder composition and the desired properties of the final part (Heaney, 2018).

Finally, in the last stage, sintering, the powder grains fuse together through high-temperature sintering to densify the part and achieve the desired final properties (Setasuwon et. al, 2008). During the sintering process, the brown parts undergo a thermal treatment aimed at bonding the metal powder, ultimately achieving high densification levels of up to 99% (German, 1996). The initial stages of sintering are characterized by mass transport mechanisms, including evaporation, condensation, surface diffusion, and volume diffusion. Subsequently, as necks form between adjacent powder particles, the dominant mechanisms shift to plastic flow, viscous flow, grain boundary diffusion, and volume diffusion (Heaney, 2018). At this stage, shrinkage occurs, typically ranging from 12% to 20%, which can vary depending on factors such as the material properties, powder characteristics (type, size, distribution), solid loading, sintering temperature, sintering time, and the quality of the initial printing (Annicchiarico and Alcock, 2014).

Upon completion of the cycle, the resulting part is transformed into a fully metallic (or ceramic, depending on the powder used) state. The density and porosity characteristics of the part are primarily influenced by the sintering step, including factors such as the temperature reached, duration of the steps, heating ramps, and control of the atmosphere. However, it is important to note that the quality of the feedstock material and the deposition strategy employed during the printing stage also contribute to the final density and porosity of the part. These factors collectively determine the overall structural integrity, mechanical properties, and functional performance of the printed object (Martin, 2022). The steps of the treatment process can be seen in Figure 6.

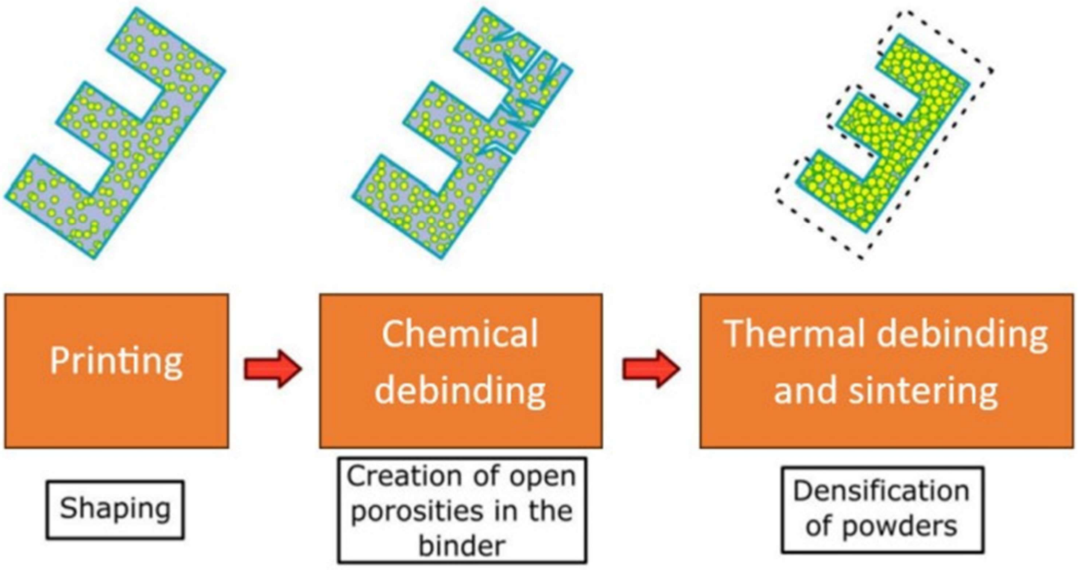

Figure 6. Treatment process for metal MEX (Martin, 2022).

4. COMPARISON BETWEEN EXTRUSION METHODS

According to Suwanpreecha (2022), a comparison of various types of extruders in additive manufacturing reveals that they employ minor differences when using the same feeding materials, leading to slight variations in performance characteristics. Table 1 focuses on the use of 17-4PH stainless steel as the feedstock, presenting a comprehensive analysis of these variations and their impact on the additive manufacturing process. The table highlights key differences in feeding material, post-processing methods, and the resulting mechanical properties of the printed objects.

In light of these considerations, meticulous attention must be given to the choice of feedstock material, particularly considering the type of extruder employed, to achieve the desired mechanical properties in the final printed part. Different materials possess varying characteristics, and selecting the appropriate feedstock is crucial to attain the desired performance and functionality. Additionally, it is essential to anticipate the shrinkage that occurs during the sintering process. This shrinkage can lead to dimensional changes in the printed part, potentially affecting its final form and fit with other components. To counteract this, designers should compensate for the expected reduction in size during the design and planning phase of the part. Properly accounting for shrinkage in the design stage ensures that the final part meets the required specifications and maintains its intended functionality.

Table 1. Material properties of the 17-4PH stainless-steel feedstock and mechanical properties of differents extruders

Type of Printing	**Binder**	**Debinding Process**	**Sintering Temperature, Time (h)**	**Shrinkage (%)**	**Relative Sintered Density (%)**	**Strength (Mpa), Elongation (%)**
Screw-based	PEG and wax	Solvent debinding in water for 12 h at 60◦C Thermal debinding in He-4% H2 at 500 ◦C for 1 h	1360 ◦C, 3 h	14.2	96.5	939.5 MPa, 3.67%
Plunger-based	Water-soluble PEG	Solvent debinding in water at 60 ◦C for 10 h	1360 ◦C for 15 h in H2 atmosphere	12.1	N/D	>1020 MPa
Filament based	Polymeric blended binder	Solvent debinding in water for 12 h. Thermal debinding in at 450 ◦C for 1,7 h.	1200 ◦C for 3 h	15	98,6	1034 MPa, 5%

5. CONCLUSION

In conclusion, this study highlights the key aspects of metal additive manufacturing using metal filaments and metal pellets, along with the subsequent post-treatment process. Careful selection of feedstock, consideration of design requirements, and optimization of printing parameters are crucial for achieving desirable outcomes. The choice between metal filaments and metal pellets should be based on specific application needs, costs, the finishing process and other factors.

Overall, metal additive manufacturing presents significant potential for diverse industries. By addressing challenges and optimizing the process, it has the capacity to revolutionize the production of metal parts, offering advantages such as increased design freedom, reduced lead times and improved functionality.

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