Review Article

Material Extrusion AM with Water-soluble Feedstocks: Background, Benefits, and Barriers

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Abstract

Material extrusion additive manufacturing (MEAM) has emerged as a versatile and cost-effective technology for fabricating complex three-dimensional components. This review focuses on the integration of water-soluble feedstocks in MEAM, highlighting their potential for environmentally sustainable and efficient manufacturing. Water-soluble polymers such as polyethylene glycol (PEG) and polyvinyl alcohol (PVA) serve as critical binder components, enabling the use of water as a debinding agent, which minimizes reliance on hazardous solvents and reduces environmental impact. The composition and optimization of feedstocks—including the balance of polymers, powders, and additives—play a pivotal role in determining rheological behavior, extrusion performance, and the mechanical properties of green and sintered parts. Challenges such as maintaining mechanical strength, managing environmental sensitivity, and ensuring consistency in processing are addressed. Key insights into the relationship between particle morphology, binder molecular weight, and process parameters such as extrusion temperature and nozzle design are meadiscussed. This paper provides a comprehensive overview of current advancements and limitations in using water-soluble feedstocks for MEAM, identifying future research opportunities aimed at enhancing process reliability and sustainability. The findings aim to support the wider adoption of MEAM in diverse applications, leveraging innovative feedstock designs for more sustainable manufacturing practices.

Keywords: Material Extrusion Additive Manufacturing (MEAM), Polyethylene.

1. Introduction

Material extrusion additive manufacturing (MEAM) constitutes a significant advancement in contemporary manufacturing, offering the capability to fabricate complex three-dimensional objects through the selective deposition of molten or viscous materials in a layer-by-layer process.
This technology is particularly advantageous due to its cost-effectiveness, versatility, and ease of implementation, rendering it suitable for rapid prototyping, tooling, and limited-scale production across diverse industries [1,2] .

1.1. Metal Injection Molding (MIM)

is an established manufacturing process renowned for its capacity to produce intricate metal components with high precision and material efficiency [3].
MIM involves the injection of a feedstock, comprising a mixture of metal powder and a binder system, into a mold cavity, followed by debinding to remove the binder and sintering to densify the part [4].
This process has proven invaluable for fabricating complex geometries that are challenging or unfeasible to machines using conventional methods.

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1.2. Use of Material Extrusion Additive Manufacturing in MIM

The convergence of MEAM and MIM technologies has engendered new possibilities for manufacturing metallic and ceramic components. MEAM techniques are increasingly being integrated into MIM processes, leveraging the advantages of both approaches [5-7]. By adapting existing MIM feedstocks for utilization in MEAM systems, manufacturers can benefit from established binder formulations and processing parameters while gaining the design freedom and customization afforded by additive manufacturing Feedstock composition plays a crucial role in both MIM and MEAM processes. Essentially, a feedstock is a meticulously balanced mixture of metal powder and a binder system [5].

1.3. Introduction to Water-soluble Feedstocks

The binder system, typically composed of polymers, waxes, and additives, is responsible for providing the requisite flow characteristics during processing, The detailed composition of typical water-soluble feedstocks is summarized in ensuring proper shape retention after deposition, and facilitating binder removal in the subsequent debinding stage. Water-soluble feedstocks represent an innovative class of materials being investigated for their potential to enhance both the environmental sustainability and processing efficiency of MEAM. These feedstocks utilize water-soluble polymers as the primary binder component, enabling the use of water as a debinding agent in lieu of harmful organic solvents. Some key water-soluble polymers employed in these feedstocks include polyethylene glycol (PEG), polyvinyl alcohol (PVA), and polyvinyl pyrrolidone (PVP)[8].

The advantages of incorporating water-soluble materials into MEAM are multifaceted. Water debinding simplifies the post-processing stage, reduces environmental impact, and supports environmentally responsible manufacturing practices[3]. Furthermore, the ability to readily remove the binder allows for the fabrication of parts with complex internal geometries and intricate features that might otherwise be challenging to achieve with conventional debinding methods. However, the utilization of water-soluble feedstocks in MEAM also presents unique challenges.

A primary concern is the potential limitation in the mechanical properties of the final sintered parts compared to those produced using traditional binder systems[9].

Additionally, the environmental sensitivity of water-soluble materials, particularly their susceptibility to moisture absorption, necessitates careful control of storage and processing conditions to maintain consistent feedstock quality[10,11].

1.4. Objectives of the Review

This review paper aims to comprehensively explore the use of water-soluble feedstocks in MEAM. The paper will examine the different types of water-soluble polymers and their properties, discuss the influence of processing parameters on feedstock behavior and part quality, and identify the key challenges and recent advancements in the field.

By providing a thorough analysis of the current state of research, this review seeks to advance the understanding and facilitate the wider adoption of this promising and sustainable additive manufacturing approach.

2. Fundamentals, Overview and Process

2.1. Fundamentals of Water-soluble Feedstocks

Water-soluble feedstocks are composite materials designed for MEAM, characterized by a binder system that can be removed with water[3,8]. This water-based debinding process offers a significant advantage over traditional binder systems that require harsh solvents or high-temperature degradation.

These feedstocks are particularly relevant in metal and ceramic MEAM, where the objective is to create complex three-dimensional objects by selectively extruding the feedstock and subsequently removing the binder to obtain a dense, solid part[8].

2.2. Basic Composition of Water-soluble Feedstocks

Water-soluble feedstocks typically consist of three main components. First, polymer binders function as a temporary adhesive, holding the metal or ceramic powders together during shaping. The binder system must exhibit suitable rheological properties for extrusion and provide sufficient green strength to the printed part before debinding. Second, metal or ceramic powders constitute the bulk of the feedstock and ultimately become the final solid object after sintering.

A wide variety of metal and ceramic powders are compatible with MEAM, including stainless steel, titanium alloys, alumina, and zirconia[12]. Lastly, additives are incorporated to tailor specific properties and improve processability. These include surfactants to enhance particle wetting and dispersion, A comprehensive overview of feedstock components and their roles is provided in Table. ***1*** resulting in a more homogeneous feedstock with lower viscosity [5], backbone polymers to provide structural support to the green part after the water-soluble binder is removed [13], and plasticizers to adjust the feedstock's viscosity and flexibility for optimal extrusion behavior[2].

Table. 1. Provides a comprehensive overview of the typical composition of water-soluble feedstocks used in MEAM, detailing the components, their percentages, and critical functions[1].

Component Category	Specific Components	Primary Function
Polymer Binders	• Polyethylene glycol (PEG) • Polyvinyl alcohol (PVA) • Polyvinyl butyral (PVB) • Methylcellulose	Provides the necessary flow characteristics for extrusion and binds the powder particles together. PEG is also easily removed during water debinding.
Metal/ Ceramic Powders	• Stainless steel (SS 316L, 17-4PH) • Titanium (Ti, Ti6Al4V) • Alumina • Zirconia • Inconel 718	Forms the structural component of the final part after sintering.
Additives	• Surfactants (e.g., Stearic Acid (SA)) • Plasticizers • Backbone polymers (e.g., Polymethyl methacrylate (PMMA), Polypropylene (PPC)) • Defoamer	Enhance the processibility of the feedstock. • Surfactants improve powder wettability and dispersion within the binder. • Plasticizers enhance flexibility and reduce viscosity. • Backbone polymers increase green strength and dimensional stability after water debinding. • Defoamers minimize air entrapment during mixing.

2.3. Overview of Water-soluble Polymers Used in MEAM Feedstocks

Polyethylene Glycol (PEG) is a linear, non-ionic polyether diol with the repeating unit -[CH_2CH_2O]-. It is highly crystalline, with a melting point that varies with molecular weight, The key properties of these polymers are compared in Table. 2. and possesses excellent water solubility due to its numerous ether oxygen atoms. PEG is completely soluble in water over a wide range of temperatures, with its solubility influenced by molecular weight. Lower molecular weight PEG exhibits faster dissolution rates. In MEAM applications, PEG molecular weights typically range from 500 to 4000 g/mol [3]. Polyvinyl Alcohol (PVA) is a synthetic polymer with the repeating unit -[$CH_2CH(OH)$]-. It is a semi-crystalline polymer with good water solubility, which is affected by the degree of hydrolysis (the percentage of acetate groups converted to hydroxyl groups).
The solubility of PVA in water is influenced by its degree of hydrolysis, temperature, and molecular weight, with fully hydrolyzed PVA having higher water solubility [11]. Polyvinylpyrrolidone (PVP) is an amorphous polymer with the repeating unit -[C_6H_9NO]-. It is highly water-soluble due to its polar amide group and is readily soluble in water and other polar solvents. Its solubility is not significantly affected by molecular weight [11].

Table. 2. Provides a comprehensive comparison of the key properties of water-soluble polymers commonly used in MEAM feedstocks [11].

Polymer Name	Molecular Weight Range (g/mol)	Water Solubility	Typical Applications
Polyethylene Glycol (PEG)	500–4000; 600–20,000 for solid PEG	Highly soluble; solubility decreases above 1000 g/mol	Titanium feedstocks , stainless steel , alumina
Polyvinyl Alcohol (PVA)	Not Specified	Partially hydrolyzed; cold water soluble	Not specified
Polyvinyl Butyral (PVB)	32,000–35,000	Soluble in water	Titanium feedstocks; alumina

2.4. Role of Water-soluble Polymers as Binders

These polymers play a critical role in facilitating the MEAM process. They provide the necessary viscosity and flow behavior for smooth extrusion through the print nozzle [14].
The polymer binder imparts strength to the printed green part, allowing it to maintain its shape and withstand the stresses of post-processing [2].
Additionally, the binder system functions as an adhesive, ensuring cohesion between the metal or ceramic particles, forming a consolidated green body [2].

2.5. Importance of Polymer Molecular Weight

The molecular weight of the water-soluble polymer significantly influences the feedstock's characteristics and performance. Table. 2. further illustrates the influence of molecular weight on polymer properties. Higher molecular weight polymers generally result in increased viscosity, which can affect the flow behavior during extrusion and may necessitate adjustments to printing parameters.
Lower molecular weight polymers offer reduced viscosity, potentially enhancing printability but may compromise green part strength [3].
While the backbone polymer primarily determines the green part's mechanical properties, the molecular weight of the water-soluble polymer can indirectly affect the part's strength by influencing the binder distribution and particle packing.
Regarding the debinding process, lower molecular weight polymers typically dissolve more rapidly in water, resulting in shorter debinding times, while higher molecular weights may require extended debinding durations or elevated temperatures for complete removal [4].

2.6. Interaction between Polymers and Powders

The interaction between the binder system and the metal or ceramic powders governs the feedstock's overall behavior. Effective wetting of powder particles by the polymer binder is essential for proper dispersion and homogeneity.
Surfactants are frequently incorporated to enhance wetting and prevent particle agglomeration, ensuring a uniform distribution of the powder within the binder matrix. The powder's particle size, shape, and surface chemistry, in conjunction with its interaction with the binder, determine the feedstock's viscosity, shear thinning behavior, and overall rheological properties, which are critical for successful extrusion.
Strong adhesion between the binder and powder particles promotes a homogeneous mixture, minimizing segregation during processing and resulting in uniform shrinkage during debinding and sintering [5].

2.7. Advantages of Water-soluble Feedstocks

Water-soluble materials, frequently utilized as binders in MEAM feedstocks, facilitate the creation of complex geometries and intricate designs. These

binders are typically combined with metal powders to form a printable feedstock [15,8].
Upon completion of the 3D printing process, the water-soluble binder is removed, leaving behind the desired metal part.
This process enables the fabrication of parts with complex internal structures and fine features that would be challenging or infeasible to achieve with traditional manufacturing methods [15]. Simplified Post-Processing and Reduced Environmental Impact: Water-soluble feedstocks offer significant advantages in post-processing.
The removal of support structures, a common requirement in MEAM to support overhanging features, becomes more straightforward with water-soluble supports.
These supports dissolve readily in water, preserving the printed part intact and eliminating the need for mechanical removal methods that could potentially damage the part [8]. Moreover, the utilization of water as the primary debinding agent significantly reduces the environmental impact compared to traditional solvent-based debinding processes. Water debinding eliminates the necessity for harsh chemicals and minimizes the generation of hazardous waste, rendering it a more sustainable approach.

2.8. Challenges and Limitations

Mechanical Property Limitations: Parts fabricated with water-soluble feedstocks can encounter challenges in terms of mechanical properties, including strength and durability.
This is partially attributable to the nature of the binder system employed.
The binder, while providing necessary flowability during printing, may compromise the final strength of the sintered metal part compared to parts produced through traditional metalworking processes [1].
a. Environmental Sensitivity Issues: Water-soluble feedstocks exhibit sensitivity to moisture. Moisture absorption can significantly affect the feedstock performance.
Exposure to humidity can lead to alterations in viscosity, potentially causing inconsistent extrusion and print quality issues [6]. Furthermore, moisture absorption can result in swelling and dimensional changes in the printed part, impacting dimensional accuracy and potentially causing defects during the debinding process [10]. Appropriate storage and handling procedures are essential to mitigate these issues [16].
b. Process Control Challenges: Maintaining consistency in extrusion and print quality is crucial for successful MEAM with water-soluble feedstocks. Fluctuations in processing parameters can lead to inconsistencies in the printed part's quality, such as dimensional inaccuracies, surface defects, and internal voids [14].
Precise control over parameters including extrusion temperature, nozzle diameter, layer height, print speed, and build plate temperature is essential to ensure reliable and repeatable printing outcomes [5].
c. Processing Parameters: The extrusion temperature significantly influences the viscosity of the feedstock. Determining the optimal temperature range is critical for successful printing. Insufficient temperature can result in high viscosity, leading to difficult extrusion and potential nozzle clogging.
Conversely, excessive temperatures can degrade the binder, leading to poor shape retention and dimensional inaccuracies in the printed part.
The relationship between temperature and viscosity requires careful optimization for each specific water-soluble feedstock [5].
d. Nozzle Diameter and Layer Height: These parameters directly influence the print resolution and material flow. A smaller nozzle diameter facilitates finer details and higher resolution but may impede material flow, particularly with highly viscous feedstocks [17].
Conversely, a larger nozzle diameter facilitates easier flow but constrains the achievable detail level. Similarly, layer height affects the resolution and surface finish of the printed part. Thinner layers result in smoother surfaces and higher resolution but necessitate longer printing times [14].
e. Print Speed and Build Plate Temperature:
The print speed influences the adhesion and overall print quality.
Excessive printing speed can result in poor interlayer adhesion and weak parts, while insufficient speed can lead to excessive heat accumulation and warping. The build plate temperature is also crucial for adhesion. A heated build plate aids in maintaining a consistent temperature, enhancing first layer adhesion and minimizing warping [18].

2.9. Debinding Process

Debinding, the process of removing the binder, is a critical step in MEAM using water-soluble feedstocks. Water-based techniques are particularly advantageous due to their simplicity, environmental compatibility, and cost-effectiveness. Immersing the printed part in a water bath dissolves the water-soluble binder, leaving the metal powder structure behind [1].
Fig. 1. The temperature of the water bath and the duration of immersion are key parameters that affect the debinding rate and the integrity of the printed part.

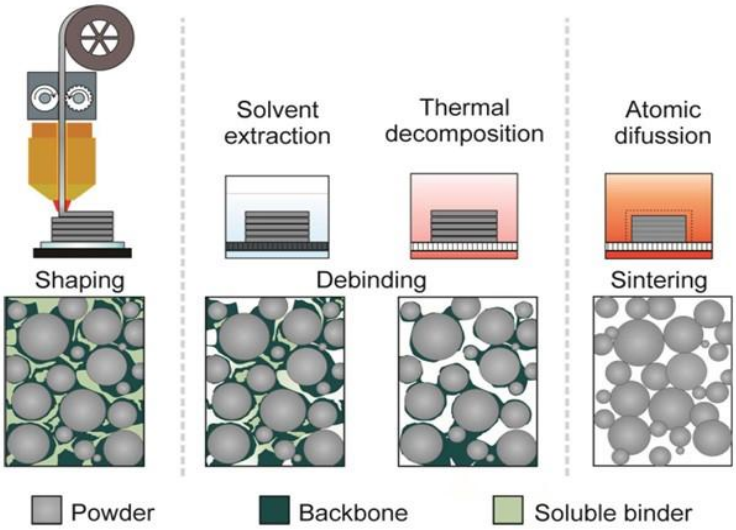

Fig. 1. Schematic representation of the shaping, debinding, and sintering [1].

2.10. Impact on Part Integrity

While effective, water-based debinding can pose risks to part integrity if not properly controlled. Rapid binder removal can lead to swelling and cracking, particularly in thicker sections [13]. It is essential to utilize appropriate debinding parameters, including temperature, time, and water quality, The schematic representation in Fig. 1. provides a clearer understanding of these stages. to ensure complete binder removal without compromising the structural integrity of the printed part [19].

In conclusion, water-soluble feedstocks offer unique advantages in MEAM, enabling the creation of complex geometries, simplifying post-processing, and promoting environmental sustainability. However, they also present challenges related to mechanical properties, environmental sensitivity, and process control. Understanding the interplay of these factors and optimizing the key processing parameters is crucial for the successful implementation of water-soluble feedstocks in MEAM, paving the way for the fabrication of high-quality, intricate metal parts.

2.11. Formulation Characteristics

Water-soluble feedstocks for material extrusion additive manufacturing (MEAM) generally consist of metal or ceramic powders, a binder system, and various additives to optimize rheological performance [15,12].

The precise composition of these feedstocks depends on the targeted material properties and the intended application. For instance, a feedstock formulation designed for 3D printing 17-4PH stainless steel exhibited a total weight loss of 6.5 ± 0.2% under thermogravimetric analysis (TGA), which indicated the binder content necessary for processability [20].

Notably, formulations originally intended for metal injection molding (MIM) have demonstrated compatibility with MEAM extrusion systems, underscoring the potential for cross-application of MIM feedstocks in additive manufacturing contexts.

2.12. Metal or Ceramic Powder

The metal or ceramic powder serves as the primary material in the final manufactured part and generally constitutes the majority of the feedstock composition (for example Fig.2 and Fig.3). The powder's characteristics including particle size distribution, morphology and specific surface area are instrumental in determining not only the rheological behavior of the feedstock but also the microstructure and mechanical properties of the final part. These properties directly influence crucial qualities such as strength, density, and surface finish.

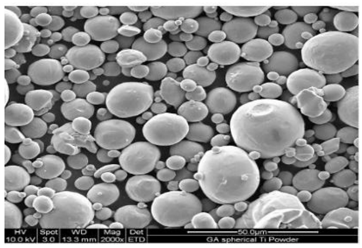

Fig. 2. SEM image of titanium [20].

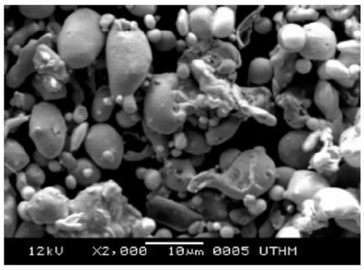

Fig. 3. SEM image of SS 316L [20].

2.13. Binder System

The binder system facilitates the feedstock's flow during extrusion and maintains the printed part's form prior to sintering.

Fig. 4. Commonly, water-soluble binders such as polyethylene glycol (PEG) and polymethyl methacrylate (PMMA) are utilized. PEG's molecular weight is particularly influential, as it affects the feedstock's viscosity and debinding properties, highlights the typical properties of water-soluble feedstocks and their influence on MEAM processes both of which are critical for the processing stability and quality of the final part [3].

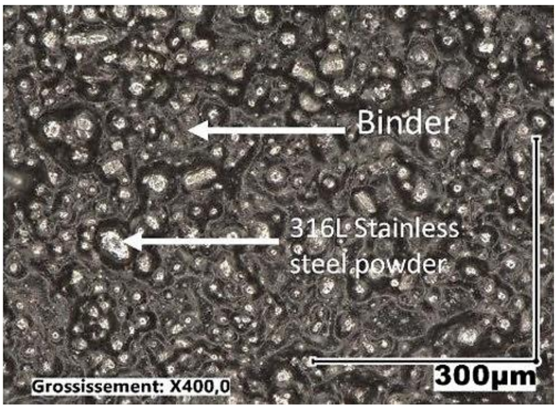

Fig. 4. Microscopic observation of part mixed with binder [3].

Table. 3. The typical composition and properties of water-soluble feedstocks used in Material Extrusion Additive Manufacturing (MEAM) [3].

Component	Typical Percentage Range	Function in Feedstock
Metal or Ceramic Powders	- 60-80 vol% (general range for metals and ceramics) - 67 vol% (titanium) - 69 vol% (titanium) - 60 vol% (titanium) - 65 vol% (stainless steel) - 61 vol% (stainless steel) - 47 vol% (zirconia)	Forms the final part after debinding and sintering.
Water-Soluble Polymer Binders	- Majority component in the binder system - 73-78 wt% of the binder system (PEG) - 83 wt% of the binder system (PEG) - 87 wt% of the binder system (PEG)	Binds the powder particles together, providing green strength to the printed part and enabling shaping.
Additives	Minor component in the binder system, typically 1-10 vol%	Modify the properties of the feedstock, enhancing processing, printability, and debinding.

2.14. Additives

Minor quantities of additives, including surfactants, dispersants, and plasticizers, are incorporated into the feedstock to enhance its rheological properties and improve final part performance. Surfactants aid in uniform powder dispersion, preventing particle agglomeration; dispersants promote mixture homogeneity, and plasticizers reduce viscosity, thus improving flexibility during extrusion [8].

The formulation of these components exerts a significant impact on both printability and final part properties.

Higher powder loading generally enhances mechanical strength and density; however, it may also reduce flowability and introduce defects. Similarly, the binder system's composition and the molecular weight of its constituents influence not only the rheological properties but also the debinding behavior and mechanical characteristics of the final part.

Additive selection and concentration provide further refinement to the feedstock's rheological behavior, stability, and resultant part characteristics [8].

The key rheological properties for MEAM feedstocks include:

a. Viscosity: Viscosity measures a fluid's resistance to flow and is critical to maintaining consistency during extrusion [17].

Optimal viscosity ensures smooth extrusion without clogging while allowing adequate shape retention post-deposition [9,14].

b. Shear Thinning: The shear-thinning property, wherein viscosity decreases with increasing shear rate, is desirable for MEAM feedstocks, as it facilitates extrusion flow and promotes shape fidelity upon deposition [17].

c. Viscoelasticity: Viscoelasticity, denoting the material's combined viscous and elastic behaviors, is crucial for predicting the extrusion response and ensuring dimensional accuracy and shape retention after deposition.

These properties significantly influence extrusion consistency and print quality. Elevated viscosity may result in inconsistent extrusion, nozzle obstruction, and compromised surface finish [9].

Inadequate shear thinning can lead to challenges in extruding fine features and maintaining shape fidelity. Poorly regulated viscoelasticity may contribute to dimensional inaccuracies and warping in the printed component.

Rheological properties can be quantified using various methodologies, including**:**

a. Capillary Rheometry: This technique measures the flow behavior of the feedstock through a narrow capillary, providing data on viscosity and shear thinning behavior [14].

b. Rotational Rheometry: This method utilizes rotating plates or cylinders to measure the viscosity and viscoelastic properties of the feedstock under controlled shear rates and temperatures(Fig. 5) [7].

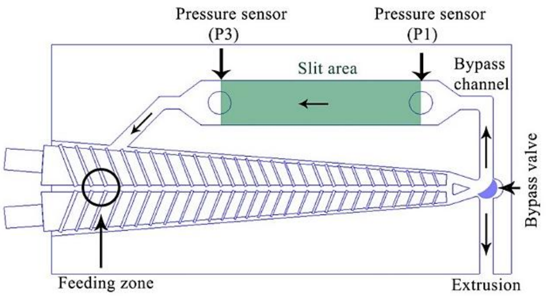

Fig. 5. Schematic illustration of the Minilab for rheological characterization of the zirconia feedstocks [7].

Optimizing rheological properties in water-soluble feedstocks is crucial for achieving high-quality prints. This can be accomplished through judicious selection of binder components, adjusting their ratios, and incorporating appropriate additives. For instance, utilizing a lower molecular weight PEG can reduce viscosity. Incorporating surfactants can enhance powder dispersion, leading to more consistent flow behavior. Modifying the processing temperature can also influence viscosity and printability [16]. In a study focusing on TI-MIM feedstocks, researchers investigated the effect of PEG molecular weight on rheological properties. They observed that increasing the molecular weight of PEG led to a higher viscosity, indicating the importance of selecting the appropriate molecular weight to achieve desired flow characteristics. Similarly, a study on water-soluble binder systems for alumina microreactors found that a higher ratio of polyvinyl butyral (PVB) to PEG resulted in higher viscosity, highlighting the impact of binder composition on rheological properties [3,21].

Key thermal properties of water-soluble feedstocks for MEAM include melting point, glass transition temperature, and thermal stability:

a. Melting Point: The melting point of the feedstock determines the extrusion temperature. The feedstock must be heated above its melting point to facilitate flow through the nozzle. The melting point of the feedstock is influenced by the melting points of its individual constituents [5].

b. Glass Transition Temperature: For amorphous binder components, the glass transition temperature (Tg) is relevant. Below the Tg, the binder exhibits brittle behavior, while above it, it transitions to a rubbery state. The Tg influences the flexibility of the feedstock at room temperature and the printing temperature.

Thermal Stability Thermal stability determines the temperature range for processing without degradation.

The feedstock should maintain stability at the extrusion temperature to prevent premature binder removal or decomposition. These thermal properties significantly affect the extrusion process, layer adhesion, and overall print quality [5]:

a. Extrusion Process: An appropriate melting point enables smooth extrusion without excessive pressure or nozzle clogging. The extrusion temperature must be sufficiently high to ensure proper flow but low enough to prevent binder degradation.

b. Layer Adhesion: The printing temperature influences interlayer bonding. If the temperature is insufficient, poor diffusion of polymer chains between layers can result in weak adhesion.

c. Overall Print Quality: Precise control of temperature throughout the printing process is essential for achieving optimal dimensional accuracy and minimizing defects such as warping or cracking.

2.15. Mechanical Properties

Green parts fabricated with water-soluble feedstocks possess specific mechanical properties that influence their handling and post-processing. These properties differ significantly from those of traditional MEAM materials, which typically utilize thermoplastic filaments without metal or ceramic powder.

a.Tensile Strength: Green parts exhibit relatively low tensile strength due to the binder's low strength compared to the sintered metal or ceramic. However, sufficient strength is necessary to handle the parts without breakage.

b.Flexural Strength: Similar to tensile strength, the flexural strength of green parts is limited by the binder.

c.Impact Resistance: Green parts tend to exhibit low impact resistance and can be brittle. The mechanical properties of green parts are primarily governed by the binder system and the degree of particle packing. Higher powder loading generally increases stiffness but reduces flexibility and impact resistance. The binder choice significantly influences the green strength and flexibility [16].

During the debinding and sintering processes, significant changes in mechanical properties occur[16]:

During debinding, the binder is removed, resulting in a porous structure. This process leads to a significant reduction in strength and stiffness.

Careful control of the debinding process is crucial to prevent cracks or distortion. Sintering; The sintering process involves heating the debound part to a high temperature, causing the metal or ceramic particles to fuse together.

Sintering leads to a substantial increase in strength, stiffness, and density, approaching the properties of the bulk material. Specific examples of mechanical properties and their changes during processing are limited in the sources. However, general trends and considerations are highlighted. For instance, research on TI-MIM feedstocks indicates the importance of selecting the appropriate PEG molecular weight to balance viscosity and debinding behavior, ultimately influencing the final part's mechanical properties.

2.16. Optimizing Feedstocks in Material Extrusion Additive Manufacturing (MEAM)

a. Surface Properties: The characterization of surface properties in water-soluble feedstock-based MEAM printed parts is essential for understanding their behavior in post-processing treatments, such as sintering or coating. The available literature, however, emphasizes the rheological attributes and compositional analysis of these feedstocks, providing limited quantitative data on surface parameters like surface roughness (Ra values) or wettability (contact angle measurements). Consequently, a comprehensive evaluation of surface properties based on the current literature is constrained, underlining a research gap in assessing these surface metrics within MEAM contexts.
b. Particle Size Distribution: Particle size distribution is a principal determinant in the formulation of MEAM feedstocks, as it substantially impacts both feedstock homogeneity and the resultant mechanical and structural properties of printed components[1,14]. Fine particles generally facilitate reduced viscosity, enhancing the flow and extrusion characteristics critical to achieving stable and precise deposition layers. In MEAM, particle sizes typically range from 5 to 15 micrometers[11]. For instance, studies on 17-4PH stainless steel powder report a particle size distribution with D10 = 3.4 µm, D50 = 11.8 µm, and D90 = 31.3 µm, which demonstrated significant improvements in feedstock uniformity and printability. In parallel, studies involving SS 316L powder report an average particle size of around 5 µm, further supporting the correlation between fine particles and enhanced feedstock performance.
The benefits of employing fine powders in MEAM are multifaceted. Fine particles support elevated solid loading, resulting in denser and more robust parts post-sintering. Additionally, reduced particle size enables the application of thinner layers during printing, which can enhance surface quality and facilitate finer geometric features in the final output [18]. Nonetheless, a critical balance is required, as excessively fine powders can increase the likelihood of nozzle clogging, presenting a trade-off between particle size and print stability.

2.17. Additive to Feedstock

a. Additives: are indispensable in modifying MEAM feedstocks' rheological and mechanical properties, optimizing them for improved processability and end-part quality. Among the most commonly used additives are surfactants, plasticizers, waxes, and thickening agents, each serving distinct functions in enhancing feedstock performance.
b. Surfactants: such as stearic acid, improve binder wettability on powder particles, leading to enhanced particle dispersion and reduced viscosity. The concentration of surfactants, optimized for powder characteristics and binder composition, is crucial to achieving ideal rheological properties [22].
c. Plasticizers: such as glycerol, are incorporated to lower feedstock viscosity, facilitating smooth extrusion flow and improved print consistency. In water-soluble systems, glycerol is particularly effective for enhancing flow behavior, reducing the propensity for defects during deposition [2].
d. Waxes: including paraffin wax, play a critical role in lowering feedstock viscosity while enhancing structural rigidity. Variations in wax type and concentration can significantly influence the thermal and mechanical attributes of the final component, with higher wax contents generally leading to improved flow but potentially reducing ductility in sintered parts [23].
e. Thickening agents: such as ethylene vinyl acetate, are also integrated to control viscosity, reducing tendencies for sagging or deformation during printing. The selection and concentration of these additives must be meticulously aligned with the binder and powder characteristics to achieve desired rheological properties conducive to MEAM processing[2].

2.18. Property Optimization

Optimizing feedstock properties is paramount in MEAM to produce high-quality, functionally robust components. The optimization process involves several key strategies:
a. Binder Selection: The binder system profoundly affects feedstock viscosity, debinding dynamics, and the properties of the sintered part(8). Water-soluble binders, such as polyethylene glycol (PEG), are preferred due to their relatively straightforward removal processes and environmental advantages [3]. The molecular weight of PEG directly influences moldability and debinding rates, necessitating precise selection based on the processing requirements [24].
b. Powder Loading: Powder loading level is integral to achieving dense, mechanically robust sintered components. Although higher powder loading typically enhances part density and mechanical strength, it also elevates viscosity, potentially complicating extrusion. Therefore, optimal powder loading levels must balance mechanical objectives with printing constraints to ensure reliable deposition and consistent structural integrity.
c. Additive Optimization: Fine-tuning the types and concentrations of additives is critical in tailoring rheological properties, including viscosity, yield stress, and shear-thinning behavior. Adjustments in additive composition can modulate processing

characteristics, enabling customization for specific MEAM applications [15,17].
Achieving an optimal balance between thermal and mechanical properties is essential during feedstock optimization. While increasing wax content may enhance flowability, it can also compromise the ductility of the final product. Similarly, higher powder loading levels contribute to improved structural strength but may introduce challenges such as shrinkage and cracking during the sintering phase [23].
A strategic approach to material and process parameter selection is therefore indispensable in realizing MEAM feedstocks optimized for application-specific performance requirements [25].In summary, material selection and parameter calibration are fundamental to advancing MEAM for complex, high-performance applications. Continued research into surface properties, particle size distribution, and additive interactions will further enhance the precision and functional versatility of MEAM-fabricated components.

2.19. Processing Parameters for Water-soluble Feedstock

Extrusion temperature: is a critical parameter influencing both the processability of water-soluble feedstocks in MEAM and the mechanical and surface properties of the final printed parts. This temperature significantly affects feedstock viscosity and flow characteristics, impacting material extrudability, the processing parameters for optimal feedstock performance are outlined in layer adhesion, and dimensional accuracy.
-typical extrusion temperature ranges:
a. polyethylene glycol (peg): 70–90°c(16)
b.Polyvinyl alcohol (pva): 190–220°c (this temperature range is based on prior data and should be validated against the specific feedstock composition and equipment requirements).
Impact of temperature on viscosity and flow behavior:
-Temperature plays a decisive role in modulating the viscosity of MEAM feedstocks. generally, an increase in extrusion temperature lowers viscosity by enhancing polymer chain mobility, which is beneficial for consistent extrusion and minimizing clogging [5]. for example, a study of 17-4ph stainless steel feedstock with a wax-based binder reported a viscosity reduction from 195 pa·s to 142 pa·s at a shear strain rate of 180 as the extrusion temperature was raised from 75°c to 85°c. a further increase to 105°c reduced viscosity to 70 pa·s, exemplifying the strong dependency of feedstock flowability on temperature.
Correlation between extrusion temperature, feedstock properties, print quality, and thermal degradation:
a. feedstock composition: optimal extrusion temperatures are heavily influenced by feedstock composition, including polymer type, molecular weight, and particle loading. peg with higher molecular weights, for example, generally requires elevated extrusion temperatures to maintain appropriate flow characteristics. higher solids loading also demands higher temperatures to achieve stable flow [7,26].
b. print quality: extrusion temperature directly affects print quality by influencing layer adhesion, surface finish, and dimensional accuracy. low extrusion temperatures can hinder material flow, resulting in poor interlayer bonding and rough surface finishes. conversely, excessive temperatures may lead to warping, delamination, or dimensional inconsistencies due to thermal expansion and contraction [12].
c. thermal degradation potential: elevated extrusion temperatures pose a risk of thermal degradation, especially for polymer binders, which may cause mechanical weakening or discoloration. degradation may also produce volatile byproducts, compromising both part quality and the working environment. therefore, the extrusion temperature must be carefully controlled to balance optimal flowability with the thermal stability of the feedstock [2].
the physical characteristics of the nozzle, including diameter, length, and internal geometry, are key determinants of print resolution, extrusion force requirements, and overall print quality in MEAM processes. nozzle diameter is a primary factor that dictates the achievable resolution of printed features. smaller diameters enable higher resolution but require higher extrusion pressures, which can increase wear on the extruder components [1]. the literature suggests nozzle diameters between 0.2 mm and 0.8 mm for MEAM applications using water-soluble feedstocks [27]. smaller diameters are generally used for high-resolution applications, while larger diameters are preferred when flow consistency and print speed are prioritized. nozzle length and geometry also affect extrusion pressure and material flow [17]. longer nozzles often result in increased pressure drop, while specific internal geometries, such as tapered or conical shapes, can help mitigate flow resistance. such designs are particularly beneficial for extruding high-viscosity, particle-loaded feedstocks, as they reduce clogging risks and enhance extrusion consistency.

3. Recommended Practices, Case Studies

3.1. Recommended Practices for Consistent Results with Water-Soluble Feedstocks

Adjusting feedstock viscosity and thermal stability improves flow consistency and print quality. Regularly calibrate printer settings for each feedstock formulation and perform test prints to prevent common issues like under- or over-extrusion.

Optimize support design considering water solubility and dissolution characteristics to enable smooth, residue-free removal. By carefully balancing print speed, layer height, and other parameters, MEAM users can achieve high-quality, detailed parts, leveraging the benefits of water-soluble feedstocks for efficient and versatile production. This attention to process parameters facilitates precise, effective use of water-soluble feedstocks, yielding strong, accurate parts suitable for a wide range of applications [1,27].

3.2. Post-processing of Water-Soluble Feedstocks

Water debinding is a critical step in processing parts fabricated using Material Extrusion Additive Manufacturing (MEAM) with water-soluble feedstocks. This process selectively removes the water-soluble binder component, typically polyethylene glycol (PEG), resulting in a porous structure that facilitates the removal of the backbone binder in subsequent thermal debinding [18]. Utilizing the principles of capillary action and concentration gradients, water debinding allows water to penetrate the part and dissolve the PEG, creating interconnected pores [3]. This method offers several advantages over other debinding methods: it is environmentally friendly, as it eliminates the need for harsh organic solvents that can harm both human health and the environment; it is cost-effective(28), given that water is a readily available and inexpensive solvent compared to specialized organic solvents; and it minimizes oxygen pickup, as the lower temperatures used in water debinding reduce the risk of oxidation in reactive metals like titanium [3].Temperature is a crucial factor governing the effectiveness and efficiency of water debinding, as it impacts the rate and completeness of binder removal, as well as the structural integrity of the final part. Research indicates that water debinding typically occurs within a temperature range of 40°C to 80°C, with the specific temperature selected based on factors like the material [24], the molecular weight of the PEG, and the desired debinding rate. Higher temperatures accelerate debinding by enhancing the molecular mobility and solubility of PEG in water [3,13], for instance, a study found that a STAINLESS-STEEL compact immersed in an 80°C water bath achieved 100% PEG removal within 12 hours. In contrast, lower temperatures slow down the debinding process. While elevated temperatures improve binder removal efficiency by ensuring the complete dissolution and extraction of PEG, exceeding the optimal temperature may soften the backbone binder, risking part integrity [28]. Extremes in temperature can also impact the part's structural soundness high temperatures may lead to rapid PEG dissolution, causing swelling and cracking, while low temperatures can result in incomplete debinding, leaving residual binder that can interfere with subsequent sintering. The risk of part deformation also rises with higher temperatures, as the binder system softens, making careful balance between debinding temperature and material thermal stability essential to prevent warping or dimensional inaccuracies[1].Selecting the optimal debinding temperature involves considering several trade-offs to achieve the desired balance between debinding rate, part integrity, and process efficiency. Factors influencing this decision include the material properties, such as the thermal stability of the part material, which dictates the upper temperature limit to prevent deformation; the binder system, as the solubility and molecular weight of the PEG binder affect the dissolution rate and the ideal temperature range(28); and the geometry of the part, where thicker parts require longer debinding times and may benefit from slightly higher temperatures to ensure thorough binder removal. Achieving the optimal debinding rate without compromising part integrity is a key challenge in the water debinding process. Higher temperatures can accelerate binder removal, yet they also increase the risk of warping, cracking, or deformation of the part. Therefore, carefully balancing the debinding rate with part stability is essential to maintain the quality of the final product [1].

3.3. Case Studies: Water Debinding Applications

Research has demonstrated the effectiveness of water debinding across various materials, underscoring the impact of process temperature on binder removal and part preservation. For instance, a study on stainless steel 316L (SS 316L) utilized a PEG/PMMA binder system and revealed that increasing the water bath temperature from 40°C to 80°C significantly accelerated PEG removal. At 80°C, 100% of the PEG was removed after 12 hours, showcasing a substantial improvement in debinding efficiency compared to lower temperatures(4). Similarly, studies on titanium compacts using the same PEG/PMMA binder system indicate that water debinding temperatures between 50°C and 70°C effectively facilitate PEG binder removal while maintaining part integrity. The research also demonstrated that increasing the temperature from 50°C to 70°C enhanced the debinding rate, leading to faster binder extraction and reduced processing times [3]. For titanium alloys such as Ti6Al4V, researchers have employed PEG/PMMA or PEG/PVB binder systems in water debinding processes. These studies indicate that a 24-hour immersion at 40°C is effective for substantial PEG removal prior to thermal debinding. This temperature allowed for significant binder extraction without compromising the structural stability of the parts, thereby supporting further processing and successful sintering [16].These case studies highlight the importance of selecting an appropriate debinding temperature based on the specific material and binder system. Optimizing the water debinding process through controlled temperature adjustments enables a balance between efficient binder removal and the preservation of part quality. Such optimization is crucial for preparing MEAM parts for successful sintering and achieving high-quality final products. The time required for effective binder removal during water debinding is a critical parameter in MEAM, as it directly influences both part quality and processing efficiency. While previous studies indicate that 12 hours at 80°C can achieve complete PEG removal in stainless steel compacts, debinding time is highly variable and dependent on factors such as part geometry, binder composition, and process temperature [4]. Part geometry, specifically thickness, affects the diffusion path length for water and dissolved binder, where thicker parts naturally require longer debinding times. For example, a study demonstrated that a 4 mm thick part took over 15 hours to reach 90% binder removal, while a thinner 0.5 mm part achieved the same binder removal in under 2 hours at 60°C[3]. Additionally, binder composition plays a significant role, as lower molecular weight PEG dissolves more readily in water, shortening the required debinding time. One study revealed that over 95% of PEG with a molecular weight of 1500 g/mol could be removed within just 6 hours, highlighting the efficiency of using lower molecular weight PEG for faster debinding. Temperature further impacts debinding rates, with higher temperatures enhancing solubility and diffusion rates of PEG, though excessively high temperatures may risk part deformation due to binder softening. Water debinding kinetics typically involve two stages: an initial dissolution-controlled stage where binder removal is governed by PEG dissolution from the part surface, and a subsequent diffusion-controlled stage where binder removal slows as the remaining PEG diffuses from the interior of the part [3]. A general mathematical model for solvent debinding, as referenced in the literature, considers debinding time as a function of factors such as part thickness, temperature, binder solubility, and the activation energy of binder solution. This model illustrates the complex interplay between material properties and process parameters, reinforcing the need for controlled debinding conditions. Monitoring the progress of water debinding is essential for process optimization and quality assurance. Weight measurements are a common approach, as the loss in weight of the part correlates directly with the amount of PEG removed. Regular weighing, combined with drying steps, enables precise tracking of debinding progress and ensures adequate binder removal before advancing to subsequent processing steps. Additionally, visual inspection can help detect surface defects such as cracks or blisters that may indicate suboptimal debinding conditions, offering further insights into process adjustments needed to preserve part integrity. Several strategies can enhance the efficiency of water debinding while maintaining part quality. Temperature control is a primary consideration, as identifying an optimal temperature for a specific binder system involves balancing the need for rapid binder removal with the risk of part deformation. Water circulation within the bath can also accelerate debinding by maintaining a consistent concentration gradient and preventing saturation of dissolved binder [28]. A multi-stage debinding approach, wherein the majority of PEG is removed through water debinding followed by thermal debinding to eliminate any remaining backbone binder, can effectively reduce overall debinding time [24].

Case studies highlight the diverse applications of water debinding across materials. For example, SS 316L compacts have been shown to achieve complete PEG loss after 12 hours at 80°C, underscoring the effectiveness of elevated temperature water debinding for stainless steel. Titanium alloys like Ti6Al4V, processed with PEG-based binder systems, demonstrate significant binder removal at 40°C after 24 hours, resulting in a high final solid content and density exceeding 99% of theoretical values post-sintering [16]. In another study on titanium, a temperature range of 50°C to 70°C facilitated effective PEG removal, with thicker parts taking longer to debind than thinner ones under the same conditions. These case studies underscore the influence of material composition, part thickness, and temperature on debinding efficacy, affirming the need for tailored optimization strategies. Although general guidelines exist, the optimal water debinding conditions are unique to each material and binder system combination, necessitating experimentation to balance debinding efficiency with part preservation.

The composition of the feedstock, particularly the binder system, significantly impacts the water debinding process in MEAM. Binder systems for MEAM with filaments, also known as Fused Filament Fabrication (FFF), frequently utilize components like elastomers or amorphous polyolefins to achieve the necessary flexibility for spooling[2]. Waxes, such as partially crystalline polyolefin wax, are also incorporated to reduce viscosity and enhance filament stiffness. The molecular weight of PEG is a critical factor that affects both the rheological properties of the feedstock and the debinding behavior[3]. Higher molecular weight PEG generally increases viscosity, which can be advantageous for extrusion. However, as PEG molecular weight increases, its solubility in water decreases, leading to slower debinding rates. This is because longer PEG chains have reduced mobility in water and increased adhesion to metal powders[3]. study found that increasing PEG molecular weight resulted in slower debinding rates. For example, feedstocks with PEG 20,000 exhibited cracking during water debinding due to the slow dissolution of the high molecular weight PEG, leading to volume expansion as water penetrated the samples faster than the binder could dissolve. This highlights the importance of choosing a suitable PEG molecular weight for successful water debinding. In general, PEG polymers with an average molecular weight between 500 and 4000 g/mol are preferred for feedstock formulations[3].

Part geometry and size also play a significant role in water debinding. Thicker parts and those with complex geometries have longer diffusion path lengths for water and dissolved binder, requiring longer debinding times. Chen et al. (2015) observed this effect, with 90% binder removal taking less than 2 hours for a 0.5 mm thick titanium part but over 15 hours for a 4 mm thick part at 60°C[13]. The size of the pores between particles also affects the debinding rate. Smaller particles generally result in smaller pores, creating a more intricate network for the dissolved binder to navigate, potentially slowing down the debinding process. This effect can be further complicated by the tendency of small particles to agglomerate, leading to defects during debinding and sintering [10].Water quality is an important consideration for water debinding. Distilled water is generally recommended to prevent impurities from interfering with the binder dissolution process. Contaminants in the water could interact with the binder or the metal powder, leading to unpredictable outcomes[11]. The sources do not provide specific information on the effects of pH and agitation on the water debinding process for PEG-based binder systems. However, it is generally understood that agitation can aid in binder removal by promoting consistent concentration gradients and preventing localized saturation[28]. Water debinding offers environmental advantages over solvent-based methods, as it eliminates the use of hazardous and volatile organic compounds. This reduces environmental risks and worker exposure. However, proper disposal of the water containing dissolved binder is necessary to prevent environmental contamination [11].After water debinding, proper drying is crucial to remove residual water and prevent defects during subsequent processing. Air drying at room temperature or using a low-temperature oven (65-75°C) for 2-3 hours is typically sufficient. Rapid drying at high temperatures should be avoided to prevent part warpage or cracking caused by the rapid removal of water[11]. Water debinding is often the first stage in a multi-step debinding process, creating open porosity that facilitates the removal of the backbone binder during thermal debinding. This interconnected pore network allows gaseous byproducts to escape during thermal decomposition, reducing the risk of defects like bloating or blistering[18].

Assessing the completeness of water debinding is essential for quality control. Methods for evaluating debinding include weight measurements, which allow for the calculation of the percentage of binder removed by comparing the weight of the part before and after debinding [13]. This simple method is commonly used to monitor debinding progress. Visual inspection can identify surface defects like cracks or blisters, which may indicate issues with the debinding process; however, this method may not be sufficient to assess internal binder removal, especially for thicker parts. Microstructural analysis with optical microscopy allows for observing the debound part's microstructure and assessing the presence of a residual binder. Chemical analysis techniques such as FTIR or GC-MS can precisely identify and quantify residual binder content, though these methods require specialized equipment[8].

The sources offer several case studies demonstrating the influence of various factors on water debinding. For example, Ibrahim[4] achieved 100% PEG removal from a SS 316L compact after 12 hours of immersion in water at 80°C. The study also investigated the effect of immersion time and temperature on the leaching performance of PEG, showing that the amount of PEG removed increased with both time and temperature[4]. For titanium alloys such as Ti6Al4V, Hanemann et al. (2020) employed a two-step debinding process using a PEG/PMMA binder system for parts produced via FFF. Water debinding was performed at 40°C for 24 hours, followed by thermal debinding[16]. The resulting parts had a solid Ti6Al4V content of 60 vol% and achieved densities exceeding 99% of the theoretical value after sintering. Additionally, Chen et al. (2015) investigated the water debinding behavior of titanium compacts using a PEG/PMMA/SA binder system, exploring the effect of debinding temperature (50-70°C) and green part thickness (0.5-4 mm) on binder removal [13]. Their results highlight the influence of part thickness on debinding time, with thicker parts requiring significantly longer times to achieve the same level of binder removal. These case studies emphasize the importance of optimizing water debinding parameters based on the specific material, binder system, part geometry, and desired outcom.

3.4. Challenges and Limitations in Water-soluble Feedstocks

The use of water-soluble feedstocks in MEAM presents several challenges, particularly concerning mechanical properties, environmental sensitivity, process control, material compatibility, and economic viability. Achieving high strength and durability in sintered parts produced with water-soluble feedstocks can be challenging due to porosity issues. The presence of residual binder from incomplete debinding is a key contributor to defects, which, in turn, can lead to reduced mechanical strength. Additionally, the mechanical properties of the final parts are influenced by the metal powder's characteristics, such as particle size distribution, as well as the sintering parameters used [1,8,18]. Despite extensive studies on debinding and processing, current literature lacks detailed data on the specific mechanical properties, such as tensile strength and elongation, for parts produced with water-soluble feedstocks. Thus, further investigation is required to fully understand the mechanical limitations associated with these materials [1].

The environmental sensitivity of water-soluble feedstocks, particularly those containing hygroscopic binders like polyethylene glycol (PEG), also presents a notable challenge. These materials tend to absorb moisture from the environment [7], which can affect their performance in various stages of the production process. Proper storage, such as using sealed containers with desiccant, is necessary to prevent moisture absorption that could degrade the feedstock. Additionally, exposure to humidity during handling and printing can alter the viscosity and flow behavior of the feedstock, leading to inconsistent print quality. Although the literature lacks specific data on moisture absorption rates for water-soluble feedstocks, studies of PEG-based feedstocks in metal injection molding indicate that even slight moisture exposure can have substantial impacts on viscosity and debinding [15].

Process control is another major challenge in the application of water-soluble feedstocks in MEAM, given the need for stable extrusion and consistent print quality. Moisture absorption can modify feedstock viscosity, resulting in uneven extrusion rates and dimensional inaccuracies. Precise environmental controls during printing, including humidity and temperature management, are essential for maintaining optimal feedstock behavior. Achieving dimensional accuracy can also be difficult due to shrinkage that occurs during debinding and sintering, along with variability in extrusion flow [8]. Surface quality is further impacted by issues such as particle agglomeration, incomplete binder removal, and inconsistent extrusion, which contribute to increased surface roughness.

Although real-world examples are limited, these process control issues are widely recognized challenges in MEAM when working with highly filled polymers, including water-soluble systems. Compatibility with a wide range of materials is also restricted in water-soluble feedstocks. Certain metal powders may chemically interact with the binder components, which can lead to degradation or contamination of the feedstock. Effective debinding of water-soluble binders without compromising part integrity is particularly challenging for high-performance metals or ceramics. Developing binder systems that can dissolve in water without affecting the material's characteristics or structural integrity requires further research [8,12].

From an economic and scaling perspective, water-soluble feedstocks may present additional challenges, especially when compared to conventional MEAM materials. While a direct cost analysis is unavailable, it is plausible that water-soluble feedstocks could incur higher costs due to specialized binder systems and increased storage and handling requirements. These factors may translate to higher processing costs and potential limitations when scaling production for industrial applications. Furthermore, implementing consistent quality control at scale may necessitate significant investments in infrastructure and process optimization, which could impact overall cost-effectiveness. The limited industrial adoption of water-soluble feedstocks suggests that achieving economic scalability remains a barrier, necessitating further research and development to improve the viability and appeal of these materials in MEAM applications [8,18].

3.5. Emerging Materials and Formulations

Research is increasingly focused on developing new water-soluble binder systems with lower decomposition temperatures for use with reactive metals like titanium. Studies are exploring binder systems combining PEG with polymers like poly (propylene carbonate) (PPC) and poly (methyl methacrylate) (PMMA) to improve decomposition control and reduce environmental impact[29]. Additionally, the impact of PEG molecular weight on feedstock rheology and debinding is being examined to achieve more uniform microstructures and minimize defects from residual binders [3]. Future research could focus on innovations in machine and extruder design to enhance control over feedstock viscosity and address sensitivity to humidity. Specialized nozzles and refined printing parameters could also improve the dimensional accuracy and surface quality of parts made with water-soluble feedstocks. Water-soluble feedstocks in MEAM may find applications beyond metals and ceramics. Potential fields include biomedical engineering, where biocompatible binders could create scaffolds for tissue engineering or drug delivery, and electronics, where removable binders could enable intricate component fabrication.

4. Conclusion

This review has examined the potential of water-soluble feedstocks in Material Extrusion Additive Manufacturing (MEAM), analyzing their composition, properties, processing parameters, debinding methods, and the challenges involved in their application. Research highlights that water-soluble feedstocks, primarily composed of polymers such as polyethylene glycol (PEG) combined with other polymers for enhanced characteristics, present a promising alternative to conventional MEAM materials. These feedstocks stand out for their environmental advantages, particularly in the debinding stage, where water serves as the debinding agent, eliminating the need for organic solvents and thereby reducing environmental impact and health risks. The quality and properties of the final part rely heavily on the processing parameters for water-soluble feedstocks, including extrusion temperature, printing speed, and layer height. Achieving optimal rheological properties, like viscosity and shear-thinning behavior, is essential for consistent extrusion and maintaining dimensional accuracy. Debinding processes, typically involving water immersion with agitation or temperature control, are carefully designed to enhance binder removal without compromising the green part's integrity.

Despite their benefits, water-soluble feedstocks face several limitations, such as mechanical property constraints, sensitivity to environmental conditions, process control challenges, and material compatibility issues. Achieving high strength and durability in the sintered parts remains a major obstacle, necessitating further research on binder formulations and optimization of sintering parameters. Additionally, the hygroscopic nature of some water-soluble binders requires controlled storage and handling to prevent moisture absorption, which can affect viscosity and lead to printing inconsistencies. Compatibility limitations with high-performance metals and ceramics further restrict the application range of these feedstocks. Recent advances in water-soluble feedstock technology include developing binder systems with improved decomposition temperatures, enhanced rheological properties, and better compatibility with a broader range of materials. Research on the effects of PEG molecular weight on feedstock rheology and debinding behavior also represents a significant step toward optimizing these materials for MEAM applications.

While the field of water-soluble feedstocks in MEAM is still developing, several areas hold promise for future research. These include creating novel binder systems with tailored properties for specific applications, optimizing processing parameters and machine design for consistent print quality, advancing debinding techniques to ensure complete binder removal, and exploring their compatibility with other additive manufacturing technologies, such as vat polymerization or binder jetting. The potential impact of water-soluble feedstocks extends beyond MEAM, aligning well with the growing emphasis on sustainable manufacturing practices. The successful development and broader adoption of these materials could reduce reliance on hazardous solvents, contribute to a cleaner manufacturing environment, and expand additive manufacturing applications in fields like biomedical engineering and electronics, where biocompatibility and easy support removal are crucial. Furthermore, the environmental benefits of these materials support a more sustainable and responsible approach to additive manufacturing, likely promoting wider acceptance across industries. In conclusion, water-soluble feedstocks represent a promising pathway for advancing MEAM. Their advantages in environmental sustainability and potential for improved performance characteristics make them a compelling area for ongoing research and innovation. Addressing existing challenges and exploring novel avenues will be vital to realizing the full potential of these materials and their transformative impact on additive manufacturing.

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