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A Review on Additive Manufacturing and 3D Printing

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ABSTRACT

Additive manufacturing (AM) and 3D printing transform production by enabling rapid creation of complex shapes, structures and products. This technology offers unprecedented design flexibility, reduced material waste and increased efficiency, impacting industries like aerospace, healthcare, automotive and consumer products. Benefits include increased design complexity, reduced material waste, faster product performance. Despite challenges like material limitations and scalability, advancements in materials and technologies will drive adoption, integration with traditional methods, emphasizing sustainability and environmental considerations.

This technology impacts various industries, offering benefits like:

• Increased design complexity

• Reduced material waste

• Faster production times

• Customization

• Improved product performance

Keywords—Additive manufacturing (AM), 3D printing, production, design complexity, material waste, efficiency, aerospace, healthcare, automotive.

1.Introduction

The ability of micron-scale additive manufacturing (AM) to produce intricate three-dimensional (3D) designs that are difficult to do with conventional lithographic microfabrication techniques has attracted a lot of interest recently. Applications in sensing technologies, lab-on-a-chip devices, mechanical metamaterials, and microelectromechanical systems (MEMS) hold particular promise for this capacity. However, methods that can create materials with optimal qualities appropriate for a wide range of applications must be developed if AM is to have a significant effect in these fields. When it comes to metals, alloying is a crucial tactic for improving mechanical strength, catalytic activity, and resistance to electromigration because pure materials frequently don't meet the necessary performance standards.

Even though alloyed materials have benefits, incorporating them into microscale additive manufacturing techniques is difficult. Existing techniques for creating small-scale metallic structures, like laser-induced forward transfer (LIFT) and ink-based sintering, provide compositional flexibility but are frequently beset by problems like substrate compatibility, high heat processing requirements, and residual porosity. Furthermore, these methods could cause undesired shrinkage or flaws that jeopardize the printed materials' structural integrity. Small-scale alloying has also been investigated using methods like focused electron beam induced deposition (FEBID), however obtaining high metal purity frequently necessitates intricate post-processing.

One intriguing method for creating dense, high-purity metal structures without the use of post-print sintering is electrochemical additive manufacturing, or ECAM. ECAM makes it possible to directly deposit metals and alloys at room temperature by utilizing easily accessible metal salt precursors. Although thin-film electroplating of alloys is a well-established process, nothing is known about how these methods might be applied to 3D microscale structures. Although recent developments have demonstrated the potential of fluid-based electroplating and meniscus-confined deposition for binary alloy systems, a flexible method for printing complex alloys with regulated composition is still missing.

In this work, we present electrohydrodynamic redox 3D printing (EHD-RP), a novel technique for micron-scale production of binary and ternary metallic alloys, which uses a droplet-by-droplet method with mixed metal salt solutions, allowing for precise control over the alloy composition regardless of the reduction potentials of the constituent metals. The use of aqueous salt solutions as ion sources simplifies the process, expands the range of printable metals, and removes the difficulties related to sacrificial anodes or intricate plating baths.

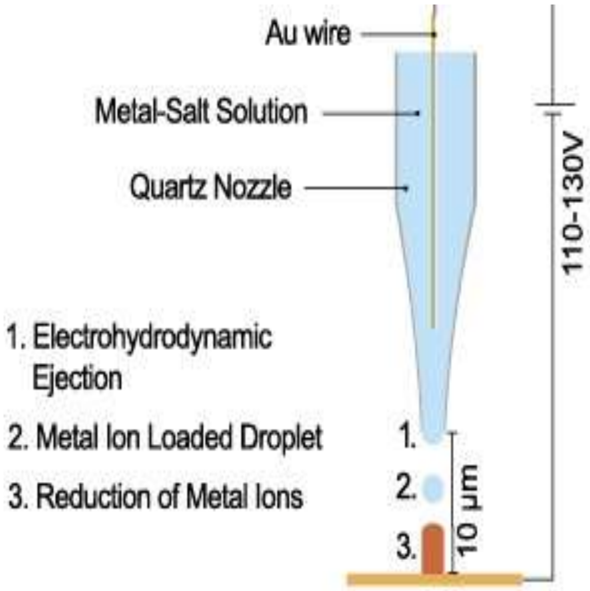

Figure1: A quartz capillary filled with an aqueous metal salt solution,

We successfully deposited ternary alloys combining Cu, Ag, and Zn as well as binary alloys like Ag-Cu and Cu-Zn to illustrate the potential of this method. According to our findings, EHD-RP is capable of creating uniform nanostructured alloys with regulated compositions throughout the alloy spectrum. The development of solid-solution phases in binary alloys and multi-phase systems in ternary compositions was demonstrated by a thorough microstructural investigation employing transmission electron microscopy (TEM). This method's adaptability creates new opportunities to tailor the characteristics of microscale metallic structures for a range of uses, including catalysis and electronic components.

2. Literature Review

The ability of micron-scale additive manufacturing (AM) to create complex three-dimensional structures that are difficult to do with conventional microfabrication methods like lithography has led to its quick development. These structures find use in lab-on-a-chip devices, sensors, microelectromechanical systems (MEMS), and other micro-scale technologies . It is still difficult to achieve the appropriate mechanical, electrical, and chemical properties in these structures, particularly when working with metallic materials. Although pure metals are frequently employed, they usually fall short of the high performance standards needed for applications requiring corrosion resistance or high strength, which has sparked a growing interest alloying.

In materials science, alloying metals to enhance their characteristics is a tried-and-true method, especially for bulk and thin-film applications. Sputtering, electroplating thin films, and bulk alloy casting are examples of conventional techniques for creating alloyed materials. It is still difficult to scale these methods for additive manufacturing down to the micron and nanoscale. For small-scale alloy synthesis, methods including focused ion beam (FIB) processing and focused electron beam induced deposition (FEBID) have been investigated. For example, FEBID can create complex structures by breaking down metal-organic precursors, but it frequently produces substantial carbon contamination, necessitating post-processing to improve purity.

By employing mixed metal salt solutions as ion sources, electrohydrodynamic redox 3D printing (EHD-RP) presents a revolutionary method for producing alloys at the micron scale. By altering the proportions of metal ions in the electrolyte solution, this method makes it possible to deposit metal alloys with regulated compositions. Although composition control was restricted to basic systems like Ag-Cu with predetermined ratios, prior work with EHD-RP has demonstrated promise in the fabrication of binary alloys. The capacity of EHD-RP to function independently of the metals' reduction potentials makes it special and permits the co-deposition of metals with radically differing electrochemical characteristics.

The range of potential alloys is increased and the production process is made simpler by using aqueous metal salt solutions in EHD-RP rather than sacrificial metal anodes. This method differs from typical electrodeposition, which frequently calls for complexing agents or complex electrolyte formulations in order to accomplish homogeneous deposition of numerous metals. There hasn't been much research done on EHD-RP's capacity to create ternary alloys by just changing the electrolyte composition. This technology offers the potential to create multi-phase alloy systems with distinctive microstructures that are challenging to accomplish with traditional methods.

Recent developments in ternary alloys, including Cu-Ag-Zn, have brought attention to EHD-RP's potential for producing materials with unique characteristics. Cu-Zn and Cu-Ag alloys with customized compositions and microstructures have been fabricated through studies, demonstrating the adaptability of EHD-RP in additive manufacturing. To completely comprehend the microstructural development of these alloys and their characteristics, more investigation is necessary. By investigating the creation of binary and ternary alloys using EHD-RP, the current study seeks to close this gap. Its main objectives are to achieve exact compositional control and comprehend the microstructural properties that arise.

3. Methodology

3.1Materials

Polylactic acid (PLA), polypropylene (PP), polyethylene (PE), acrylonitrile butadiene styrene (ABS), hydroxyapatite, metal powders, titanium alloys, cobalt-chromium alloys, stainless steel, Mn Zn ferrites, graphene, carbon nanotubes, ceramic resins, PEG-based materials, photopolymers, silica nanoparticles, para wood powder, PVDF, ferroelectric materials, conductive carbon grease, recycled plastics, WEEE-derived polypropylene, Mg-Zn alloys, electrically conductive polymers, polymer nanocomposites, lithium cobalt oxide, plant-based fats, and other biodegradable polymers.

3.2 Steps involved in 3D printing of an object

describes the procedures involved in creating a real 3D printed item. First, a virtual 3D structure is designed in silico using computer-aided design (CAD) software. An estimate of the projected structural integrity of the final product is also given by the CAD program. The CAD file must then be converted to STL (Standard Tessellation File) format. The fundamental principle of tessellation is to transform the produced 3D model's 2D outer surface into tiny triangles called "facets," which are in charge of characterizing the surface geometry.

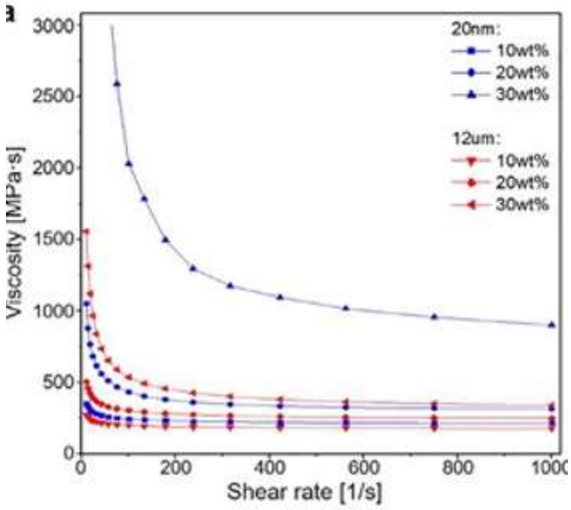

Figure2: Influence of shear rate on paste viscosity with different solid content

Table-1

Factor	Variable	Type	+ 1 Level	-1 Level
A	UV layer exposure time (s)	Continuos	0.6	0.3
B	UV post curing time (min)	Continuos	3	10
C	Baking temperature (°C)	Continuos	80	100
D	Sonication Power (%)	Continuos	0	100
E	Pillar width (μm)	Continuos	50	100
Fixed Factors				
F	Baking Time (min)	Continuos	30	
G	Sonication Time (min)	Continuos	30	
H	Aspect Ratio	Continuos	10	
I	Layer Thickness (μm)	Continuos	50	

fixed factors and factors examined in process optimization. The experiment was conducted using a 25 complete factorial design, where all possible factor combinations were taken into account during the experimental trials and each component was modified through two levels. Above the table is the full model equation that was produced using this design. It should be noted that only terms with a significant level of $p \leq 0.1$ were taken into account for each particular yield; as a result, some of the terms given may not be present in the model equation.

show two distinct thresholds: the Bonferroni limit and the crucial t-value, which is based on the student's-t distribution and has a 5% significant level. The latter is always greater than the critical t-value and is a family-wise adjusted t-critical value, where fewer words are considered significant since the t-value is calculated by lowering the significance threshold to account for the number of tests conducted. An analysis of variance (ANOVA) test was conducted to confirm the empirical model's significance as well as that of the chosen terms: as a As a result, irrelevant terms were dropped. The model was deemed significant only if it was within the 95% confidence interval (95 % CI, $p<0.05$), whereas terms were deemed significant if they were within the 90% CI, $p<0.1$. To account for the unpredictability of the process components and, consequently, to identify their effect, a 90% confidence interval (CI) for the terms and a 95% CI for the model were used. If necessary, a function was applied to the yield (F(Y)) to make the residual patternless and regularly distributed.

4. Applications

4.1 Microelectromechanical Systems (MEMS)

EHD-RP is appropriate for producing MEMS components because it can create complex, high-resolution, micron-scale metal structures. These systems need accurate, small components that can take use of alloyed metals' mechanical strength and conductivity, such as micro-actuators, sensors, switches. Alloys such as Cu-Ag and Cu-Zn produced via EHD-RP can offer improved performance in terms of durability and electrical conductivity, which are critical for MEMS applications.

4.2 Sensors and Sensing Platforms

Because EHD-RP can print metals with specific compositions and properties, it can be utilized to produce extremely sensitive micro-scale sensors. For chemical and biological sensing, for example, arrays of micro-pillars composed of copper or silver alloys can increase surface area. For certain uses where improved catalytic or plasmonic qualities are required, such as gas sensors, pressure sensors, or biosensors, alloyed structures can be tailored.

4.3 Lab-on-a-Chip Devices

The manufacture of miniature parts for lab-on-a-chip systems—which combine several laboratory operations onto a single chip—is made possible by the accuracy of EHD-RP. These devices are appropriate for microfluidic channels, electrodes, and integrated circuits because they take use of the electrical and corrosion-resistant qualities of printed metallic alloys. By offering adaptable qualities like chemical resistance and biocompatibility, ternary alloys like Cu-Ag-Zn can further improve the performance of lab-on-a-chip systems.

4.4 Mechanical Metamaterials

The creation of mechanical metamaterials with special qualities not present in bulk materials is made possible by the capacity to print complex 3D microstructures with high aspect ratios. By altering the metal composition, these metamaterials can be made to have adjustable stiffness, strength, flexibility. Customization of metal microstructures can lead to applications in fields such as energy absorption systems, impact-resistant materials, and lightweight structural components.

4.5 Electronics and Microelectronics

EHD-RP is appropriate for the production of microelectronic components due to its capacity to deposit metals with exact geometries and excellent conductivity. This comprises antennas, micro coils, and interconnects—all crucial components for tiny electronic systems. By lowering resistance and increasing electromigration resistance—two essentials for dependable high-speed electronic devices—direct deposition of copper and silver alloys can enhance microelectronic circuit performance.

4.6 Catalytic and Plasmonic Applications

Effective catalysts for chemical reactions can be produced from printed metallic microstructures with customized alloy compositions. For instance, Cu-Ag alloys are well-known for having increased catalytic activity, which can be used in environmental cleanup, hydrogen production, and fuel cells, among other uses. Surface-enhanced Raman spectroscopy (SERS) and other optical sensing methods can make use of alloyed micro-pillars in plasmonic applications by improving their optical characteristics.

5. Conclusion

The efficiency of electrohydrodynamic redox 3D printing (EHD-RP) as a flexible and accurate method for creating micron-scale structures of binary and ternary metallic alloys is demonstrated in this work. EHD-RP makes it possible to deposit alloys with regulated compositions droplet by droplet using mixed metal salt solutions, regardless of the reduction potentials of the individual metals. Many of the drawbacks of conventional additive manufacturing (AM) techniques are addressed by this approach, including ink-based approaches that necessitate intricate post-processing and sintering-based methods that are prone to porosity and thermal damage.

The spectrum of printed materials and compositions is increased by the direct fabrication of high-purity metal structures from aqueous salt solutions. With exact control over the alloy ratio, our tests effectively proved the deposition of Cu, Ag, and Zn as well as alloys like Cu-Ag, Cu-Zn, and Cu-Ag-Zn. The possibility of microscale material property customization was shown by the microstructural investigation, which showed the creation of multi-phase systems in ternary alloys and homogeneous mixing in binary alloys.

By offering a versatile, effective, and highly adjustable method of creating intricate geometries and structures, additive manufacturing (AM) and 3D printing have completely changed the manufacturing industry. AM constructs components directly from digital models, layer by layer, in contrast to conventional subtractive manufacturing techniques, which depend on removing material from a solid block. Unprecedented design freedom, less material waste, and quick prototyping and production of end-use parts across multiple industries are all made possible by this creative approach.

The capacity of 3D printing to create complex and lightweight structures that were previously unfeasible or prohibitively expensive using traditional techniques is one of its biggest benefits. In industries including consumer goods, automotive, healthcare, and aerospace, where there is a growing need for high-performance, lightweight, and customizable parts, the technology has demonstrated tremendous promise. For instance, the development of patient-specific implants, prostheses, and dental equipment made possible by AM in medical applications has significantly improved patient outcomes.

Additive manufacturing has many advantages, but in order to reach its full potential, certain issues must be resolved. Material constraints, surface quality, mechanical characteristics, and scalability are still important research and development topics. To increase AM's potential, materials science must continue to progress, especially in the creation of new metals, polymers, ceramics, and composite materials. To make AM more competitive with conventional manufacturing processes on a wider scale, post-processing procedures must be optimized, and 3D printer speed and accuracy must be increased.

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