# Interface Fusion in Multi-Material Additive Manufacturing Technology

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**Abstract.** Multi-material additive manufacturing lets different materials combine in three-dimensional space. This makes it possible to create complex parts. These parts can have custom properties. Such properties meet specific functional needs. The quality of interface fusion directly affects the final part's performance and reliability. To solve this problem, many technical methods have been developed. This paper reviews interface fusion in three common multi-material additive manufacturing techniques. These techniques are material extrusion, material jetting, and photopolymerization. Based on their formation mechanisms, the study found and grouped the main types of interactions at these interfaces. These types include mechanical interlocking, molecular or atomic diffusion, and chemical bonding. The next sections explain in detail the characteristics of each interface type. The discussion includes design strategies to improve material compatibility. Relevant systems are ceramic matrices, thermoplastic polymers, and metal-ceramic composites. This paper gives a complete summary of active control methods for multi-material interfaces. Key techniques are optimizing multiple process parameters, adjusting material formulas, and planning coordinated printing paths for different materials. The conclusion shows the future research needed to overcome current challenges in the field.

**Keywords:** Multi-material additive manufacturing; Interface fusion; Mechanical interlocking; Chemical bonding; Performance regulation

## 1 Introduction

Additive Manufacturing (AM) has changed traditional manufacturing methods. This shift has greatly altered how products are designed, developed, and made. Today, the technology is widely used in many fields, such as aerospace, automotive, and medical devices [1]. AM is popular for several key benefits. It provides high precision, offers great design freedom, and eliminates the need for molds. It can also reliably produce highly complex parts. Techniques like Material Jetting (MJ), Direct Ink Writing (DIW), and Fused Deposition Modeling (FDM) can directly produce functional components. Additive Manufacturing can create parts like intralayer, interlayer, gradient, and nested multi-material structures. This is done by loading nozzles with equal amounts of the required material [2–5]. However, most AM processes cannot produce parts made of multiple materials at once. As a result, extra assembly steps are often

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needed to combine different materials into one product. Yet, many applications depend on using a mix of materials to function correctly. Therefore, achieving integrated multi-material manufacturing is a crucial next step. This advancement will allow additive manufacturing to fully realize its potential in this area.

Multi-Material Additive Manufacturing (MMAM) lets us print parts using different materials in one process. This technology is useful in many areas. These include soft robotics, composite materials, and electronic devices [6–8]. This paper looks closely at the interface fusion problem in MMAM, based on recent studies. Some progress has been made in making the shapes correctly. But there are still major gaps in the science behind it. We do not fully understand how the bond forms in three dimensions. We also need to connect the printing process to the final part's strength. Another issue is planning the toolpath to make the interface stronger. By reviewing existing research, this paper tries to build a clear theory that links the process to the material's properties. This theory is important. It helps move additive manufacturing from just shaping objects to controlling their properties. It also supports new advances in fields like soft robotics, electronics, and biomedical devices

## 2 Material Extrusion Technology for Multi-Material Interface Fusion

### 2.1 Mechanism of Interface Formation

The way multi-material interfaces form can differ greatly. These differences come from using various processes and materials. The main bonding methods involve mechanical interlocking, molecular or atomic diffusion, and chemical bonding.

Mechanical interlocking happens when one material physically anchors into another. This occurs through shapes and structures that fit together at the interface [9]. This mechanism does not rely on interactions at the atomic or molecular-level. Instead, it works by the materials' geometries locking together. This lock allows forces to be transferred, which makes the bond stronger.

Mechanical interlocking is a common and effective bonding method. It is especially important for material systems where metallurgical bonding is hard to achieve. Experts generally agree that this method usually works together with diffusion or chemical bonding. This combination creates a stronger composite effect [10–11]. Mechanical interlocking includes both macro-scale and micro-scale types.

Macro-interlocking uses specially designed 3D shapes that lock together. This has been shown to greatly improve the bond at the interface. For example, Shi et al. took inspiration from biological structures [10]. They used selective laser melting to create a Gyroid structure on a copper substrate. Then, they filled this mold with A356 aluminum alloy via vacuum infiltration casting. This formed a strong "mortise-and-tenon" macro-mechanical lock. This continuous 3D network stopped cracks from spreading along the interface. As a result, the shear strength was much higher than that of traditional lattice structures or flat interfaces. Micro-interlocking refers to the mechanical interlocking effect provided by the material's inherent porosity, surface roughness, or micro-anchoring points introduced through subsequent processing. For instance,

Hu et al. employed laser powder bed fusion (LPBF) technology to construct a sawtooth interlocking interface spanning from the micron to the nanometer scale in W/CuCrZr functional gradient materials. The dual-scale mechanical interlocking, synergistically combined with metallurgical bonding, ensured the material's exceptional interfacial shear strength [11,12].

For thermoplastic polymer interfaces, intermolecular diffusion is the main bonding mechanism. The PLA-PETG interface studied by Richter et al. follows a contact-wetting-diffusion model [13]. Here, PC melts at 280°C, which causes the PLA surface to wet at 205°C. Because their Hansen Solubility Parameters match, the molecular chains can diffuse. This diffusion depth can reach up to 80 nm, creating a gradient interface. In contrast, for PP-PVA, the Hansen Solubility Parameters are very different. The distance is 18.3. This large difference prevents diffusion. As a result, a clear and separated interface forms. During cooling, thermal stress plays a major role. For example, PE and PLA have very different Coefficients of Thermal Expansion. This difference creates a thermal stress of about 120 MPa. Such high stress can easily cause microcracks to form.

### 2.2 Key Material Systems

**Ceramic Matrix Composite Systems.**Wick-Joliat et al. investigated two key ceramic composite systems. These are colored $ZrO_2$ ceramics and electrically conductive $MoSi_2/Al_2O_3$/feldspar composites [12,13]. For the $ZrO_2$ system, a commercial Ceramic Injection Molding binder was used. It had a solid loading of 51.3 vol%. After sintering at 1450°C, the parts reached a high density. Their density was 96.4–96.6% of the theoretical value. Because of this high density, the material is suitable for bioceramic prosthetics. The $MoSi_2$ system consists of 17% $MoSi_2$, 33% $Al_2O_3$, and 50% feldspar. It was sintered at 1250°C in an argon atmosphere. This process gave the material a low resistivity of $10^{-3}$ Ω·cm. Due to this property, it can be used to make high-temperature heating elements.

**Thermoplastic Polymer Systems.** The interfacial bonding strength varies a lot. These material combinations can be split into three groups. These groups are highly compatible, moderately compatible, and poorly compatible [13]. For highly compatible pairs like PLA-PETG and PETG-PC, the interfacial bond is very strong. It can be close to or even higher than the strength of the base materials. Because of this, the material itself often breaks before the bond does in strength tests. Moderately compatible pairs, such as Nylon-PVA, can also get good bond strength. But their performance is not steady. This is mainly because PVA absorbs moisture easily. This moisture affects the result. Poorly compatible pairs include materials like PE and PP. They have very low interfacial bonding. Their bond strength is often nearly zero. In practical use, PETG-PC works well in high-temperature environments, like electronic enclosures. This is because it has good heat resistance. On the other hand, PLA-PETG is a better choice for everyday consumer parts

### 2.3 Strategies for Controlling Interface Properties

Wick-Joliat et al. studied ceramic printing that uses granulate feedstock. Their key methods to control interface performance were managing the temperature gradient and adjusting the material formula [12]. The printing process was divided clearly into three stages, each with a different temperature. In the upper zone, air cooling was used to prevent the feedstock from clogging. The central zone was heated to 70°C to soften the binder. The lower main heating

zone was set at 160°C to make sure the material melted and extruded evenly. For the $ZrO_2$ feedstock, the extrusion temperature was 160°C and the printing speed was 20 mm/s. The $MoSi_2$ feedstock was more viscous. Because of this, the settings were changed to a lower extrusion temperature of 130°C and a slower printing speed of 16 mm/s. This change helped to reduce clumping of particles at the interface. For the material choice, the Embemould K83 binder was selected. This binder works well because its polar groups can form hydrogen bonds with the hydroxyl groups on $ZrO_2$ particles. The amount of $MoSi_2$ was varied between 10 and 17 vol%. At 17 vol%, the composite became electrically conductive. At 10 vol%, it acted as an insulating support material. The resulting interface bonding strength was about 15 MPa.

Richter et al. studied how to control the bonding between polymers [13]. They looked at three main factors. Thermal history, material compatibility, and interface microstructure. First, they examined thermal history. They found that a higher nozzle temperature helps. For example, a temperature of 280°C for PC lowers the material's viscosity. This better flow improves wetting and diffusion at the interface, which makes the bond stronger. Next, they studied material compatibility. The research used Hansen Solubility Parameters (HSP) and thermal expansion (CTE) to predict compatibility. Materials with very similar HSP values and matched polarity had the strongest bonds. Sometimes, the material itself broke before the bond did. In contrast, materials with very different HSP values and low polarity had much weaker bonds. Finally, they observed the interface microstructure. They saw two different types. One was a gradual, blended gradient interface. The other was a sharp and distinct line. The gradient type appeared when materials were highly compatible. This shows that bonding at the nanoscale, through wetting and diffusion, is what mainly controls the quality of the interface.

## 3. Material Jetting Technology for Multi-Material Interface Fusion

### 3.1 Mechanism of Interface Formation

The liquid-solid co-printing technology investigated by Brandon et al. focused on the utilization of liquid as a printable support medium, thereby facilitating the single-step fabrication of complex structures [14]. In this process, photocurable polymer microdroplets impacted the surface of a non-photocurable liquid, spread due to a positive spreading coefficient, and subsequently solidified upon UV curing. The newly formed solid layer adheres to the surrounding pre-deposited and cured resin matrix through a process known as photopolymerization. The primary function of liquid support is to serve as a provisional morphological interface, thereby preserving overhanging or intricate geometries prior to the curing process.

In the study by Zschippang et al., the interfacial fusion type is characterized by glass-phase bonding coupled with mechanical interlocking, with local chemical interactions also present [15]. During sintering at 1800°C, $RE_2O_3$ (a mixture of $Y_2O_3$ and $Yb_2O_3$) and $SiO_2$ form a low-melting glass phase that fills the gaps between $Si_3N_4$, SiC, and $MoSi_2$ particles, bonding them together. Concurrently, the particles undergo slight deformation at elevated temperatures, resulting in the formation of a physically interlocked structure. It has been demonstrated that at a pressure of 6 atm, no additional chemical reactions occur. However, at 31 atm high nitrogen pressure, $MoSi_2$ reacts with $N_2$ to form the $Mo_{4.8}Si_3C_{0.6}$ phase. While this process entails local

chemical bonding, it concomitantly degrades the original interfacial bonding and interlocking integrity.

In the design by Gamba et al., the interfacial fusion type is physical packing combined with mechanical interlocking [16]. 80 nm Al and 80 nm CuO particles are deposited via aerosol jet printing. In the context of a static mixing printhead, the gas flow exerts a force that causes the particles to divide and subsequently re-combine, thereby leading to uniform dispersion and physical packing of the two distinct types of particles. Following a drying process at 95°C for 60 minutes, the removal of the organic solvent is achieved, and the particles are then adsorbed by van der Waals forces. The irregular morphology of the particles results in slight mechanical interlocking. The interfacial porosity is less than 5%, and no chemical bonds are formed.

### 3.2 Key Material Systems

The key material systems involved in this technology comprise structural materials and liquid support materials [14]. A variety of structural materials have been developed to meet the respective requirements for various components in microfluidic devices. These materials include highly transparent VeroClear, rigid VeroCyan, and the flexible TangoBlack+. They are used for observation windows, primary structural components, and flexible sealing or valve membranes. The liquid material is a polyethylene glycol-based model cleaning fluid with a density similar to that of the photocurable resins. Its surface tension temporarily supports the resin microdroplets during the curing process. Subsequent to the printing process, this liquid support material can be readily eliminated through a straightforward fluid flushing procedure (e.g., with water), obviating the necessity for elevated temperatures or corrosive solvents. This approach ensures the preservation of the integrity of intricate internal channels and multi-material structures.

Zschippang et al. focused on ceramic composites made via Multi-Material Jetting. The key material system is divided by function into conductive and non-conductive types [15]. The conductive material contains 23 ma% $Si_3N_4$, 46 ma% $MoSi_2$, 18 ma% SiC, 2.5 ma% $SiO_2$, and 10.5 ma% $RE_2O_3$. After sintering, it reaches a density of 4.400 g/cm³ and a resistivity of $10^{-2}$ Ω·cm. These properties make the material suitable for high-temperature heating elements. The non-conductive material contains 53 ma% $Si_3N_4$, 33 ma% $MoSi_2$, 1 ma% SiC, 2.5 ma% $SiO_2$, and 10.5 ma% $RE_2O_3$. After sintering, its density is 4.184 g/cm³, and its volume resistivity exceeds $10^6$ Ω·cm. This allows it to be used as an insulating support structure.

Gamba et al. prepared nanothermites using Aerosol Jet Printing. Their material system mainly consists of a functional phase and a solvent [16]. The functional phase is made of Al nanoparticles and CuO nanoparticles. These are mixed at the 2Al+3CuO stoichiometric ratio. The reaction enthalpy reaches 1547 J/g, which meets the requirement for high energy release.The solvent is a mixture of 40% isobutyl acetate, 40% diglyme, and 20% Cyrene. Its surface tension ranges from 27.7 to 30.6 mN/m. This formulation matches the atomization needs of the printing process. As a result, particles disperse evenly and deposit stably.

### 3.3 Strategies for Controlling Interface Properties

Zschippang et al. employed 6 atm nitrogen pressure during sintering to suppress the formation of the $Mo_{4.8}Si_3C_{0.6}$ phase, thereby preserving the glass-phase bonding and mechanical interlocking structure and increasing the $MoSi_2$ retention rate to 88 %. In the debinding stage, a

heating rate of 5 K/h up to 450°C was employed to reduce carbon residues and prevent the reaction of carbon with $SiO_2$ to form SiO and CO. The prevention of these reactions is crucial as they would otherwise damage the glass phase and ensure interfacial bonding performance [15].

Gamba et al. changed their printing setup. They replaced a T-junction with a static-mixing printhead [16]. This new design increased the contact area between the Al and CuO materials by 3 to 5 times. The better contact improved how closely the particles packed together. It also strengthened the mechanical interlocking between them. Another result was a faster reaction. The ignition delay time dropped from 200 milliseconds to just 130 milliseconds. The team also adjusted the flow rates of the carrier gases. For the Al ink, the flow rate was set to 8 sccm. For the CuO ink, it was set to 15 sccm. They made this change because CuO is less efficient to atomize. The different flow rates helped spread both types of particles evenly. This ensured the interface performed at its best.

## 4. Photopolymerization Technology for Multi-Material Interface Integration

### 4.1 Mechanism of Interface Formation

The formation mechanisms of multi-material interfaces exhibit significant differences due to variations in preparation processes, with most involving chemical bonding.

At interfaces, chemical bonds are formed through covalent, ionic, or metallic bonds, which are considered the strongest form of bonding. In metallic systems, this phenomenon predominantly manifests through the formation of stable intermetallic compounds via interfacial reactions.

The bionic structural design developed by Wu et al. was predicated on a dual mechanism of physical interlocking and chemical bonding at the interface [17]. The $Al_2O_3$ ceramic scaffold fabricated via vat photopolymerization (VPP) exhibits micrometer-scale pores on its surface, while the 316L stainless steel surface printed by powder bed fusion (PBF) presents a rough structure due to unmelted powder particles. In the presence of negative pressure, the epoxy resin infiltrant permeates both the ceramic pores and the interstices on the metal surface. It forms a strong chemical bond with $Al_2O_3$, with an interfacial bonding energy of -1058.60 kcal/mol, while simultaneously establishing mechanical interlocking with the unmelted powder on the 316L surface. This process ultimately resulted in the formation of a three-layer ceramic-resin-metal interface.

In the study by Bergoglio et al., the interface in multi-material biobased epoxy systems is formed primarily through mechanical interlocking, which arises from a combination of molecular chain entanglement and the surface roughness between layers [18]. It is noteworthy that both ELO (epoxidized linseed oil) and DGEVA (vanillin alcohol diglycidyl ether) contain epoxy groups. Under the same cationic photoinitiating system, during the dual-vat DLP printing process, adjacent resin layers undergo secondary crosslinking via the incompletely cured epoxy groups. It is evident that no discernible new phase is generated at the interface; bonding is entirely dependent on chain entanglement. In addition, the presence of a modulus mismatch between the

aromatic ring structure of DGEVA and the flexible, long chains of ELO leads to the manifestation of a gradient adhesive characteristic at the interface.

### 4.2 Key Material Systems

In order to address the growing demand for high-toughness structures, Wu et al. have developed a novel $Al_2O_3$-316L-epoxy resin system [17]. The $Al_2O_3$ ceramic (a blend of 100 nm / 500 nm powders with 3 wt.% MgO as a sintering aid) provides hardness and wear resistance. The 15–35 μm spherical 316L stainless steel powder contributes to the material's toughness, while the epoxy resin functions as an interfacial compatibility phase. The volume fractions of the three components were optimized to 41.81 %, 10.98 %, and 47.21 %, respectively, achieving a flexural strength of 220.2 MPa and a fracture toughness of 21.97 $MPa \cdot m^{1,2}$.

Bergoglio et al. developed a sustainable biobased system called ELO-DGEVA [18]. ELO has a long-chain fatty acid structure. Because of this, its modulus is low (505 MPa) and its glass transition temperature is also low (52°C). In contrast, DGEVA has an aromatic ring structure. This gives it a much higher modulus (1615 MPa) and a significantly higher glass transition temperature (96°C). The formulation included two key additives. First, 0.02 phr of Sudan II was added to control light absorption. Second, 2 phr of iodonium salt was used to start the cationic polymerization. This system is fully biobased, achieving 100% bio-content. Furthermore, the printed multilayer structures can show shape memory behavior. This means they change shape in response to temperature changes.

Chen et al. tried to make a material that was both light and impact-resistant [19]. They suggested a composite material with $Al_2O_3$, $TiO_2$, and 7075 aluminum alloy. To build a strong framework, they used $Al_2O_3$ powder. This powder had particles of two sizes. The sizes were 5 μm and 50 nm. The team added 5 wt.% $TiO_2$. This addition helped improve bonding during sintering. It made the reactions at the interface stronger. It also increased the final density. 7075 aluminum alloy was also added to the composite. This greatly strengthened the metallic part of the composite. The team made the material in two main steps. First, they sintered it at 1650°C. Then, they did a melt infiltration process at 780°C. The final composite has a density of 3.35 $g/cm^3$. Typical carbon steel has a density of 7.85 $g/cm^3$. This means the composite is about 58% lighter. Achieving such a low density is important for lightweight design goals. The composite also works well in mechanical terms. It absorbs energy very well. Its specific energy absorption per volume (SEAV) is 41.39 $MJ \cdot m^{-3}$. For comparison, a structure made of pure aluminum has an SEAV of 23.69 $MJ \cdot m^{-3}$. The composite's SEAV is 1.75 times higher. These results show the material has excellent impact resistance and energy absorption.

### 4.3 Strategies for Controlling Interface Properties

Wu et al. looked for ways to improve the bond between materials [17]. Their strategy combined two ideas. One was designing a better interface shape. The other was controlling how epoxy resin flows into it. They created a unique three-dimensional rounded interlock. This design helped distribute stress more evenly. It also lowered the stress concentration at the interface. For the epoxy process, they used specific settings. The temperature was set at 95°C. A vacuum of –80 kPa was applied. These settings let the resin fill all gaps completely. Some unmelted powder remained on the 316L metal surface. This made the surface rougher. The roughness improved

mechanical gripping. These combined actions made the interface much stronger. The resistance to debonding went up by about 37 percent.

Bergoglio et al. improved the material's performance by optimizing the formula and controlling printing precisely [18]. They found that adding 1 phr of ITX photosensitizer worked best. This amount reduced the curing time difference between ELO and DGEVA to about 2 seconds per layer. When both materials cured at a similar rate, internal stress was avoided. Normally, stress happens if one material hardens faster than the other. The printing chamber was kept at 50°C. This temperature allowed DGEVA to flow. DGEVA is solid at room temperature. It also prevented ELO from softening too much. These combined adjustments strengthened the final multilayer structure. The interlayer shear strength reached 18.2 MPa. This value is 25% higher than the strength when printing at room temperature.

## 5. Conclusions

This review focuses on a key problem in multi-material additive manufacturing. The problem is interface fusion. It summarizes recent research from three main processes. These processes are material extrusion, material jetting, and photopolymerization. The analysis shows both the advances and the current limitations. It finds that interfaces form in different ways. The effects of these ways together are often complex. For material extrusion, bonding usually depends on mechanical interlocking. In ceramic systems, bonding happens through melt wetting and physical locking of particles. For polymers, the process is different. Bonding here relies on how compatible solubility parameters are. This compatibility lets molecular chains move across the interface. Material jetting puts down and cures droplets layer by layer. This method often uses liquid support materials. The supports hold parts in place during printing. This helps create interlocking structures. Photopolymerization mainly depends on chemical bonding and matching shapes. At metal-ceramic interfaces, transition phases can form. For bio-based resins, functional groups can crosslink. A single bonding method is often not enough for high-performance parts. A combined method works better. Strong interfaces usually come from a mix of mechanical interlocking, diffusion, and chemical bonding. Progress in interface properties depends on specific material systems. In ceramic systems, high density and strength are achieved with optimized binder formulas and sintering aids. Thermoplastic polymers are grouped based on their bonding compatibility. For pairs with high compatibility, the material itself may break before the interface does. For pairs with low compatibility, added compatibilizers make the bond stronger. In metal-ceramic systems, phase design can increase fracture toughness. We do this by combining compatible hard and soft phases. A multi-dimensional framework now helps improve interface performance. This framework brings together several strategies. These strategies work with each other. The three main strategies discussed here show a big change in approach. The focus is no longer just on dealing with interface problems as they happen. Now, the interface is actively designed from the start to get better performance.

This proactive method gives a practical way to adjust material properties for different uses. The dynamic processes at material interfaces are not yet fully understood. Future studies using advanced technologies can lead to more accurate methods for predicting how these interfaces evolve. Current strategies for interface control still have limited applicability. There is an urgent

need to develop universal control techniques suitable for gradient materials. At the same time, research into adaptive interface design should be pursued. Such interfaces could use external stimuli like temperature or stress during use to repair defects on their own. This capability would significantly improve the long-term reliability of structures. Progress in application areas will further drive this field forward. Key sectors include aerospace, biomedicine, and electronic devices. Innovations in these areas are expected to advance additive manufacturing technology. The focus will shift from producing single-material shapes to customizing the performance of parts made from multiple materials.

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