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Review

Additive Manufacturing in Australian Small to Medium Enterprises: Vat Polymerisation Techniques, Case Study and Pathways to Industry 4.0 Competitiveness

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Abstract: The advent of additive manufacturing (AM) in Australian small and medium-sized enterprises offers the direct benefits of time-saving and labour cost-effectiveness for Australian manufacturing to be highly competitive in global markets. Australian local businesses can tailor their products to a diverse range of customers with a quicker lead time on the sophisticated design and development of products under good quality control in the whole advanced manufacturing process. This review outlines typical AM techniques used in Australian manufacturing, which consist of vat polymerisation (VP), environmentally friendly AM, and multi-material AM. In particular, a practical case study was also highlighted in the Australian jewellery industry to demonstrate how manufacturing style is integrated into their manufacturing processes for the purpose of reducing lead time and cost. Finally, major obstacles encountered in AM and future prospects were also addressed to be well positioned as a key player in the revolutionised Industry 4.0.

Keywords: additive manufacturing (AM); vat polymerisation; environmentally friendly additive manufacturing; multi-material additive manufacturing; Industry 4.0

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1. Introduction

Additive manufacturing (AM), otherwise known as 3D printing, is a layer-by-layer building approach to constructing 3D objects [1,2]. AM can produce complex components in contrast with conventional subtractive manufacturing, such as computer numerical control (CNC) and milling, where internal geometry is limited to tool size with less complex shapes or geometry [2]. The flexibility of the AM process has allowed engineers and designers to achieve greater design freedom and customisation since manufactured parts can be incredibly complicated and meet the specific requirements for specialised tooling [3]. AM mainly focuses on prototype manufacturing for the friendly use of householders, simplified supply-chain management for businesses, and cost-effectiveness and material waste reduction on specialty products [4]. AM gradually leaps from its prototyping phase and has entered the critical phase where real-life component manufacturing occurs either on-site or off-site. It has been estimated that worldwide AM-related revenues will reach USD 23 billion by 2027, which is considered a major player in Industry 4.0 [4].

The estimated value of Australia's complete AM (or 3D printing) market amounts to approximately USD 70 million according to the International Trade Administration [5]. In view of contemporary manufacturing technologies, Australia's reputation as an early technology adopter is not prominent, causing its demand to trail behind other international commercial markets such as Japan and Korea. Nonetheless, Australia tends to swiftly embrace new technology once it gains the momentum, and the forthcoming five years are projected to witness a rising trend towards professional and industry-scale 3D printing solutions [6].

Manufacturing sectors in Australia constitutes 6% of the Gross Domestic Product (GDP) [5]. These domains have already become well-established markets for 3D printing solutions. Additional prevalent applications within Australia include automotive sectors (primarily within the aftermarket domain), architectural ventures, medical services, and dental undertakings. To a greater degree, Australian businesses leverage 3D printing primarily for prototyping and conceptual modelling. Although some applications are extended to the industry-scale production of functional parts, this practice remains limited in scope. Notably, the outsourcing of 3D printing services is still predominant for industrial and commercial purposes [5].

The growth of 3D printing in Australia is amplified due to high labour costs and geographical constraints, leading to a potential shift in business models from traditional manufacturing to a major focus on design and direct-to-consumer services [7,8]. Stratasys completed a survey of over 700 professionals worldwide in AM sectors and found the top four current challenges most companies encounter when adopting AM technologies are equipment costs, limited materials, manufacturing costs and post-processing requirements [9]. Figure 1 shows a downturn in vat polymerisation (VP) techniques into the future due to these critical issues, while Figure 2 shows major areas where Australian manufacturers are currently using AM technologies.

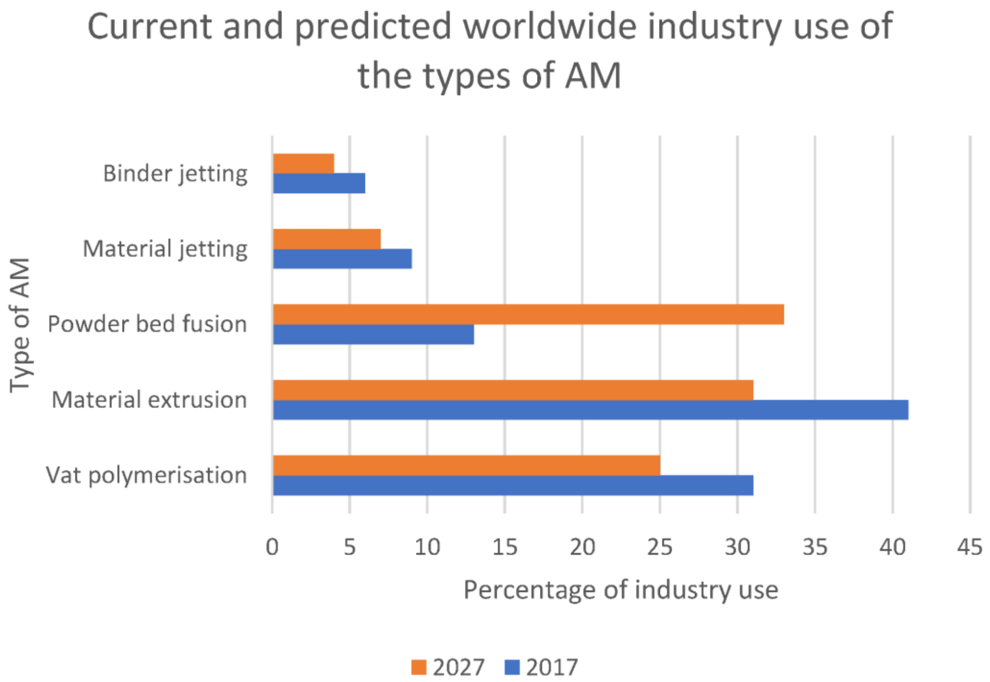

Figure 1. Percentage of revenue earned in the professional industry shows material extrusion such as fused filament fabrication (FFF) and fused deposition modelling (FDM) falling behind powder bed fusion (PBF). Vat polymerisation (VP) continues to fall in popularity due to a lack of diverse material availability and post-processing requirements [7–9].

On the other hand, machine tool distributors are steadily incorporating 3D printing solutions into their array of applications. However, existing 3D printing distributors in Australia tend to focus primarily on solutions and accessories related to 3D printing [10]. The market encompasses a relatively modest number of distributors, often holding exclusive affiliations with foreign manufacturers [5]. Typically, one distributor becomes the official or exclusive representative of a foreign entity, thereby directly catering to resellers and end-users. An influential catalyst for the advancement of 3D printing within the next decade will be driven predominantly by consumer usage and demand [11]. The projected expansion of the consumer-oriented market is anticipated to surpass the projected growth in commercial sectors [12]. Manufacturers are poised to adapt their business models to accommodate emerging distribution channels and direct competition from self-printing consumers. This shift might also involve catering to a burgeoning community of designers and entrepreneurs to shape innovative ideas and products. Research indicates that more and more traditional manufacturing entities might transition into virtual businesses, prioritising the sale of intellectual property and idea generation to consumers rather than focusing solely on end products [12].

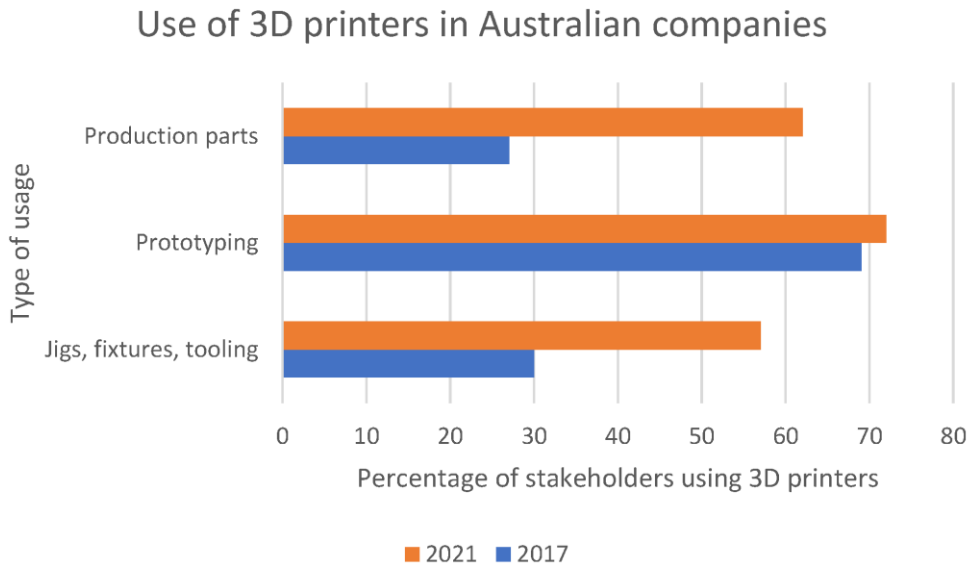

Figure 2. Companies are diversifying their 3D printing applications, as seen by an increase in the uptake of production parts [8]. Within the market's segments: Metals surged by 25% to USD 4.9 billion (AUD 7.3 billion), polymers increased by 20% to USD 7.3 billion (AUD 10.9 billion), software stood out as the fastest-growing segment, valued at USD 1.2 billion (AUD 1.8 billion) in 2022, and AM services were accumulated to a worth of USD 6 billion (AUD 9 billion) [7]. Market projected to more than double by 2026, estimated at USD 37.2 billion in 2020, and 54% of engineering firms escalated their functional end-use parts printing [8].

It might take several years for current technological constraints to be overcome in 3D printing. However, Australia is poised to undergo profound disruptions with respect to 3D printing for a couple of compelling reasons [12]:

- The country's elevated labour costs have prompted the outsourcing of manufacturing, rendering local production comparatively expensive;
- Australia's vast size and remote location result in higher international and domestic costs in logistic chains, prolong transit periods, and necessitate higher inventory levels due to the substantial distances that goods must traverse;
- As a developed nation with relatively robust disposable income, the demand for personalised goods is expected to be higher in Australia than in less developed countries.

It is noteworthy for larger companies to consider the potential to leverage 3D printing for the reduction of supply chain expenditures. Nevertheless, the removal of a significant entry barrier to the capacity for manufacturing (or sourcing manufacturing) may pose a risk of intensive competition.

AM-based products can be used for various industrial applications, including consumer goods and services, building and construction, military and aerospace engineering, as well as energy and medical devices [13,14]. The cost-to-complexity ratio in AM refers to the relationship between the cost of producing a part or product using AM processes and the complexity of a design [15]. It essentially assesses how the intricacy or complexity of a design impacts the overall cost of production in AM compared to traditional manufacturing methods. In the latter, producing intricate or complex designs often requires complex tooling, specialised moulds, and intricate machining processes, which can significantly increase production costs. However, AM has the unique ability to create complex geometries and intricate structures without the requirement for complex tooling changes. This can result in cost savings for complex designs, as the same AM process can produce both simple and complex parts with relatively consistent costs [15]. However, notwithstanding such a benefit, AM currently equips manufacturers with the capability of producing small batch sizes or highly personalised products [15]. The cost-to-complexity ratio in AM can have several implications, as seen in Table 1. It is important to note that the cost-to-complexity ratio can vary based on factors such as material selection, technology, part size, production volume and available equipment. A thorough cost analysis that considers these factors will help determine whether AM is the most cost-effective choice for a specific application based on design complexity.

Table 1. Implications of the cost-to-complexity ratio in AM [15].

Cost-Effectiveness for Complex Designs	AM can be cost-effective for parts with intricate designs since the layer-by-layer approach used in this manufacturing process allows for the establishment of complex shapes and internal structures without substantially impacting production costs. This makes AM particularly attractive for industries such as aerospace, medical devices and custom manufacturing.
Reduced Tooling Costs	Traditional manufacturing often requires expensive moulds and tooling to create complex shapes. AM eliminates the demand for changing tooling, which can reduce initial setup costs and lead time for manufacturing complex parts.
Design Freedom	AM enables designers to create complex, lightweight and optimised structures that are not feasible when using traditional manufacturing methods. This freedom allows for innovation and improved product performance in widespread applications.
Material Usage and Waste	Although AM offers typical advantages for complexity, it can be less cost-effective for producing large volumes of simple parts due to material costs and build time. Traditional manufacturing may be more efficient in such cases.
Post-Processing and Finishing	Complex designs produced via AM might require post-processing steps to achieve the desired surface finish or mechanical properties. These additional steps can add to the overall cost and time.
Economies of Scale	While AM offers direct benefits for complex and low-volume production, traditional manufacturing methods may become more cost-effective owing to increased production volumes in accordance with economies of scale.

Vat polymerisation (VP) is an AM process where a liquid resin, cured by the irradiation of a particular wavelength, is used to form a 3D shape [16] and will be the main focus of this review. Once curing is completed, the resin turns into a thermosetting material with typical characteristics of high brittleness and low mechanical performance due to the smaller length of polymeric chains, as well as the requirement of high-viscosity resins [3,17]. The small length of polymeric chains induces poor mechanical properties in resins owing to their anisotropic behaviour and typical issues concerning material limitations, microstructures, layer adhesion, interfacial bonding and post-processing steps [3,18,19]. Resins particularly used in AM are required to possess low viscosity for easy material flow under the build plate and to increase AM print resolution for stereolithography (SLA) and digital light processing (DLP) [17]. The easy material flow of resins is critical to generating AM structures layer-by-layer with fine layer thickness and self-levelling features [20]. Figure 3 demonstrates the relationship between low-viscosity resins for improved resolution and printing and their higher-viscosity counterparts to enhance mechanical properties but accelerate resin degradability [20]. The crosslinking network is formed due to the diluent concentration and chain length interactions of photopolymers. As such, degradability is reduced in lower-viscosity resins as the lower polymeric chain length will crosslink to a higher degree [20]. As more diluents are added such as vinyl-based monomers, the non-degradability of the crosslinking part increases accordingly [20].

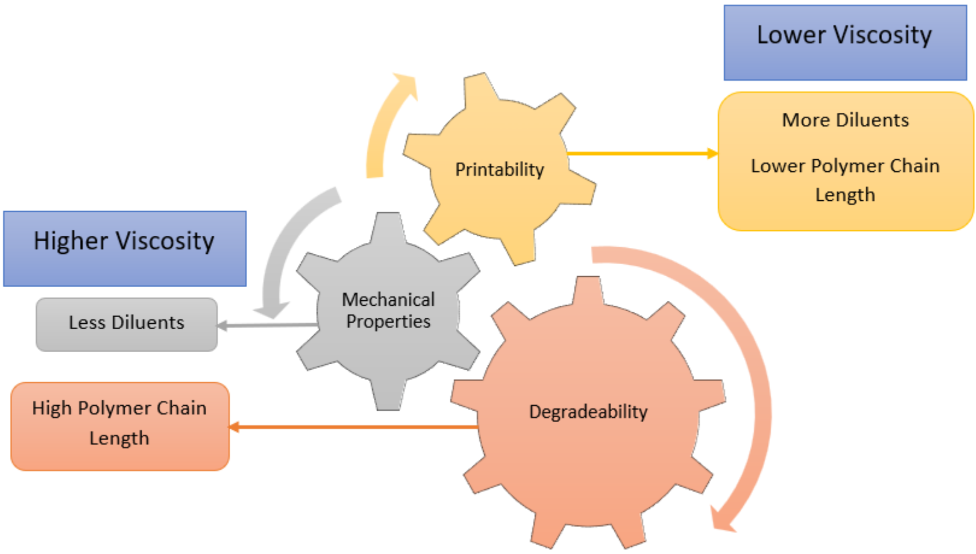

Figure 3. Relationship between resin viscosity, printability, mechanical properties and degradability [16].

Other additive manufacturing techniques that can be used by industries are given as follows:

- Selective laser sintering (SLS) employs a high-powered laser to fuse powdered materials, including polymers and metals, in a layer-by-layer manner. This process benefits from its capacity to manufacture functional and durable parts with complex geometries, making it ideal for wide-scale industrial applications such as aerospace, automobiles and medical devices [21]. SLS is particularly useful in creating end-use components, rapid tooling and parts with internal structures that are difficult to produce through traditional manufacturing methods such as machining, extrusion, injection moulding, etc. Its ability to work with a wide range of materials, including engineering-grade plastics and metals, positions SLS as a versatile solution for various applications;
- Fused deposition modelling (FDM), also known as fused filament fabrication (FFF), involves extruding thermoplastic filaments layer by layer to build up a part. This process is widely used due to its simplicity and cost-effectiveness. FDM is applicable across diverse industries such as consumer goods, automobiles and aerospace. It is used for rapid prototyping, functional testing and the production of end-use parts like jigs, fixtures and customised tools. A wide range of available materials are used in FDM, including high-performance plastics and composite filaments, to further enhance its adaptability to diverse applications [21]. Its accessibility and ease of use have contributed to its popularity for both professional and hobbyist applications;
- Binder jetting (BJT) involves the deposition of a liquid binder onto powdered materials such as metals, ceramics, or sand on a layer-by-layer basis. This process is particularly suitable for producing sand moulds and cores used in metal casting, architectural models and intricate components [22]. BJT offers cost-effective production of complex geometries and prototypes. Industries benefit from its ability to create parts in a wide range of materials, making it versatile for specific applications in aerospace, automobiles and construction. Post-processing steps, comprised of sintering or infiltrating the parts with additional materials, improve their strength and durability;
- Direct metal laser sintering (DMLS) and selective laser melting (SLM) employ a high-powered laser to selectively fuse metal powders layer by layer, producing fully dense metal parts with intricate designs [21]. These processes are pivotal in industries like aerospace, medical implants and automobiles because they allow for the creation of lightweight and high-strength components that are otherwise challenging to manufacture. The ability to work with a variety of metals such as titanium, aluminium

and stainless steel contributes to their applicability in critical fields requiring both precision and strength. The capability of manufacturing complex geometries and customise parts for specific needs by using DMLS and SLM makes them game-changing technologies in modern manufacturing;

- Electron beam melting (EBM) employs an electron beam to selectively melt metal powders (often titanium alloys) in a vacuum environment [21]. This process excels at producing intricate and strong components, making it indispensable in industries such as aerospace and medical implants. Vacuum conditions in EBM result in particular parts with fewer voids and improved material properties, thus ensuring biocompatibility for medical implants and structural integrity for aerospace components. The ability of EBM to create parts with minimal residual stress and better material utilisation significantly contributes to its reputation for high-quality and high-strength production;
- PolyJet printing employs inkjet heads to deposit liquid photopolymers layer by layer. It enables the creation of multi-material and multi-colour objects with fine details and smooth surface finish [22]. This process is extensively used in producing prototypes with realistic textures, medical models for surgical planning and intricate consumer products. The capability of PolyJet to simulate different material properties within a single part makes it valuable for design validation and functional testing. Its versatility and ability to replicate complex assemblies with ease contribute to a wide range of applications across various industries;
- Laminated object manufacturing (LOM) involves layering and bonding sheets of material such as paper or plastics using heat or adhesives [2]. This process assists in producing large models and architectural prototypes with the use of low-cost tooling. Its affordability and capability to create full-scale models make it a preferred choice in industries like architecture, product design and entertainment. Its simplicity and suitability for creating functional prototypes with reasonable accuracy have made it a practical option for rapid prototyping and iterative design processes;
- Gas metal arc welding (GMAW), commonly known as metal inert gas (MIG) welding, is a versatile and widely used welding process. It involves the use of a consumable electrode wire that continuously feeds into the welding arc while a shielding gas is used to protect the weld area from atmospheric contaminants [23]. GMAW is preferred for its ease of use, high deposition rate and the ability to weld a variety of materials, which is deemed an essential technique across diverse industries. GMAW further expands its use in the manufacturing and fabrication of metal products across industries [23]. It is commonly employed in the production of structural components, machinery and industrial equipment due to its efficiency and versatility.

These additional AM processes showcase a diverse range of techniques available to transform design concepts into tangible objects. From applications of BJT in casting to the strength of DMLS/SLM, the precision of EBM in metal parts, the multi-material intricacy of PolyJet to the practicality of LOM for large-scale prototypes, these technologies are reshaping industries by enabling innovative design, rapid prototyping and cost-effective manufacturing.

There are, however, several knowledge gaps to fill before AM can take a leading role in contemporary manufacturing for small and medium businesses. The creation of a sustainable future for 3D manufacturing and rapid prototyping technologies for both small and medium businesses would greatly benefit Australian manufacturing by reducing manufacturing costs and allowing them to directly manufacture where wages are higher than those in surrounding countries [24]. This has identified several current AM techniques and issues regarding small to medium-sized manufacturers and proposed future perspectives concerning VP, multi-material additive manufacturing, and topology optimisation im order to increase the AM uptake in Australian small businesses.

The main objective of this review is to comprehensively analyse and evaluate critical issues surrounding the adoption of 3D printing technology within Australian industries by exclusively investigating a case study in Western Australia. Through an exploration of the challenges and opportunities encountered, it aims to provide valuable insights into potential benefits, typical limitations and specific strategies required for successful integration of 3D printing in various sectors in order to benefit the overall Australian economy.

2. Vat Polymerisation Techniques

Vat polymerisation (VP) remains one of the most accurate AM processes, with a printing resolution in the order of tens to hundreds of micrometres and an excellent surface finish [3,25]. The parts produced from the VP method can be used for prototypes and end-use parts, as well as employed instead of wax for investment or lost wax casting methods [15].

Investment casting, or lost wax casting, is a technique to turn wax or resin patterns into metal objects. This method has several stages, and it is widely used in the jewellery, medical and transportation industries. AM has allowed for the easy creation of a resin pattern that would have been previously made of wax or clay. Jewellers, equipped with specialised skills, traditionally carve a wax pattern from a wax block. For jewellery purposes, once the pattern was completed, it would be attached to a central wax stem called sprueing, which usually exists with other patterns [26]. The sprue allows the molten metal to flow into the mould, and extra wax components can be attached to the system, called gates or vents, to allow the metal to flow smoothly along with the air escape [19]. The sprue is then coated in a ceramic refractory material with a binder made from gypsum or phosphate for jewellery or medical casting in order to create a shell called an investment mould [26]. All air must be removed from the ceramics in a degassing phase to prevent any deformities or imperfections in the mould [26]. After the investment mould has been manufactured, it is placed in a high-temperature kiln to melt away the wax pattern or allow the resin to turn to ash, resulting in a hollow cavity. Once the pattern has been fully removed, molten metal is poured into the casting under controlled conditions. The mould must be evenly cooled to avoid imperfections in the pattern, and the investment must be cracked open or dissolved to reveal the cast once cooled [26].

The following section will introduce three VP techniques, namely SLA and DLP, as the two most popular techniques, and continuous liquid interface production (CLIP), a newcomer in the VP field, to meet current manufacturing challenges.

Photocuring polymers via SLA is the earliest developed technology and has expanded into many different techniques, including DLP and continuous liquid interface production (CLIP) [16]. The central concept of 3D resin printing is photopolymerisation. This process involves the controlled transformation of liquid photopolymers into solid structures when exposed to specific wavelengths of light [1]. Photopolymers are composed of molecules that react to light and become cross-linked and hardened when subjected to an appropriate wavelength [17,27]. This property is regarded as the cornerstone for layer-by-layer fabrication in resin-based AM. In this process, a polymerisation reaction forms the solids from a liquid resin by crosslinking or forming polymeric chains. The photoinitiator (PI), when exposed to light, becomes a catalyst to promote chain formation between monomers and oligomers [27,28].

Gibson et al. (2021) [2] and Pagac et al. (2021) [27] explain how standard photopolymers used in VP for 3D printing are divided into the following three main components:

- Monomers: These are small and reactive molecules enabling the polymerisation upon their light exposure. Monomers used in photopolymers typically contain double bonds that can initiate the polymerisation process when exposed to UV light;
- Oligomers: Oligomers are larger molecules composed of multiple monomer units, which contribute to mechanical properties of final printed objects. Oligomers can enhance the strength, flexibility and overall stability of polymers;
- PIs: PIs are compounds that absorb UV light and then release the energy as the activation of a polymerisation process. They facilitate the cross-linking effect of monomers and oligomers, leading to the formation of a solid polymer network.

These components are combined in specific ratios to create a photopolymer with desired mechanical, thermal and optical properties.

Light penetration is crucial across all printing methods since it impacts the absorption and transmission of light through photoresins [29]. Consequently, this process affects the generation of reactive components along the light's path, thus influencing the transformation from liquid to solid, which is a phase referred to as the gel point. In printing methods that operate layer by layer, the depth of penetration dictates the presence of layer-related anomalies [1]. Conversely, in layer-less construction using volumetric printing, the depth of penetration determines whether adequate light dosage reaches across the complete width of the vat [29]. The relationship between cure depth, laser exposure dose and light penetration depth is established through the Beer−Lambert equation [29] as follows:

$$C_d = D_p ln\left(\frac{E_{max}}{E_c}\right) \tag{1}$$

where C_d is the cure depth, D_p is the depth of light penetration through the resin, E_{max} is the light exposure dose, and E_c is called the gel point where the resin can receive the critical exposure dose. Being illustrated on a semilogarithmic graph as C_d against $ln(E_{max})$, the distinctive "working curve" of photoresins emerges to be in a linear relationship. This curve, varying among different photoresins, can be used to calculate individual values of D_p (slope) and E_c (intercept) [29]. This equation holds pivotal importance in ascertaining the ideal light exposure for each material in order to avoid excessive or insufficient curing, reduce layer irregularities, and uphold consistent cure depth and layer proportions across various resins.

SLA uses a moveable laser or ultraviolet (UV) light for resin polymerisation in a point-by-point pattern generated by a computer-aided design (CAD) programme [1]. The CAD programme prepares a 3D printable object by creating 2D slices called layers [30]. The computer programme moves the build plate to form a thin resin film between the build plate and the resin reservoirso that the vertical distance of layer size can be achieved [2]. Such a resin is then cured by the laser or UV light, and the build platform moves up again to allow for the flow of resins underneath, as illustrated in Figure 4.

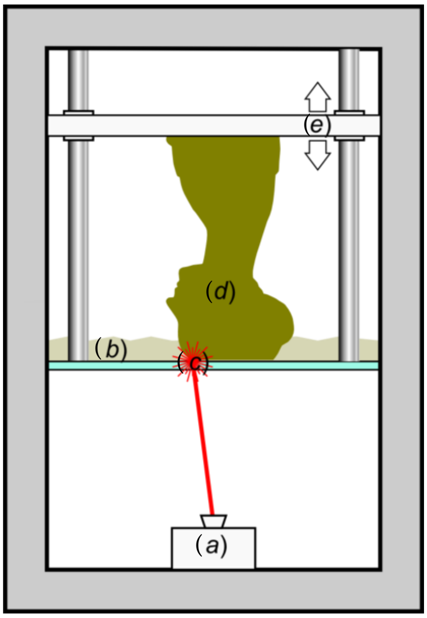

Figure 4. Schematic diagram of a SLA process. (**a**) laser or UV light device; (**b**) resin reservoir that has a clear film on the bottom to allow the light emitting device to cure the resin; (**c**) light emitting device curing the thin film of resin between the bottom of the resin reservoir and the solidified part of the 3D build; (**d**) the solidified part of the 3D build being lifted by the build platform; and (**e**) the printing platform. Paolo Cignoni, CC BY-SA 4.0.

Similar to SLA, DLP employs a computer to slice a 3D component into 2D slices [2]. However, DLP projects the full sliced image onto the build area using a projector [31–34]. Figure 5 shows the process of bottom-up DLP printing, where the printing platform is immersed in the resin contained in the resin tank and sits one layer thickness above the release liner. The projected image then passes through the transparent glass layer and further cures the resin [15]. The printing platform is lifted, and the platform must move vertically away from the liquid resin to allow for the next layer to be relocated by new resin flowing underneath and its settling evenly [15,31].

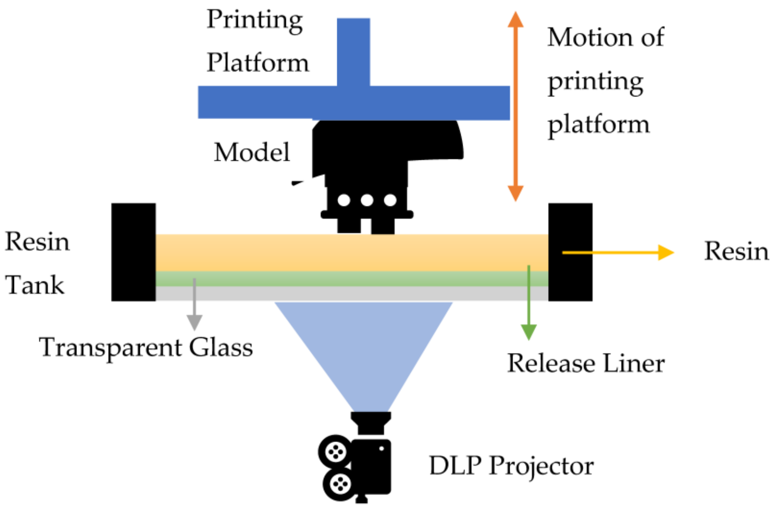

Figure 5. Schematic diagram and working procedure of a DLP print [31].

One of the drawbacks associated with the VP technique lies in its slow production speed due to the layer-by-layer approach to building the high-resolution print [14]. Continuous liquid interface production (CLIP) uses a high-performance projector to project the UV light of the sliced image in a 3D model onto the underside of the liquid vat in order to hold the resin-like DLP [1,14]. However, with the addition of controlled oxygen to inhibit resin curing, models can be built much faster without layers when combined with light projection [14]. The oxygen allows for a faster build by forming a "dead zone" of uncured resin between the bottom of the vat and the part being built, as seen in the yellow part of the resin vat in Figure 6. After washing off the excessive amount of resin, the second step in the CLIP process is to bake the model in order to achieve desired mechanical properties [14].

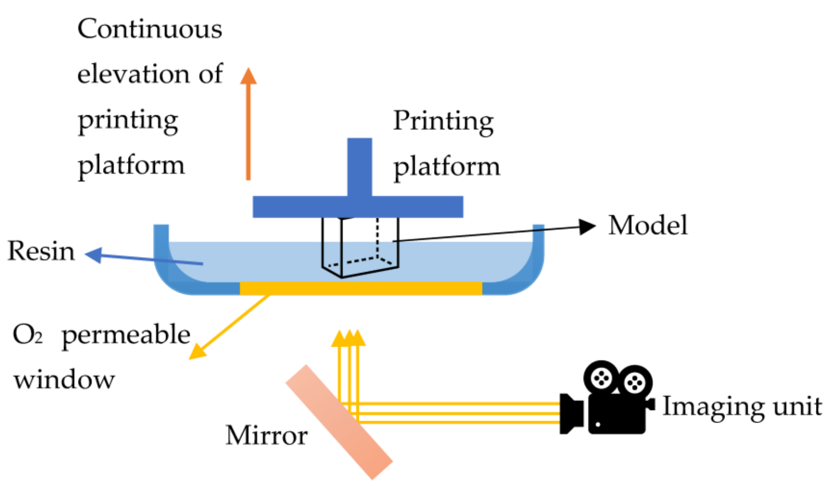

Figure 6. CLIP process shows layerless printing and the architecture of a CLIP printer [14].

The selection of SLA, DLP, or CLIP technologies significantly influences the use of suitable materials due to the distinct characteristics and operational mechanisms of individual technologies. In particular, the use of SLA or DLP can affect the materials chosen according to Table 2.

Table 2. The influence of different types of materials on VP technique [2,14].

VP Technique	Benefits	Impact on Material Choice
Stereolithography (SLA)	Laser Precision: SLA employs a UV laser to cure photopolymers layer by layer, allowing for high precision and intricate detail in the final printed object. Material Compatibility: SLA generally requires the solidification of photopolymers under UV light exposure. These resins can be customised with various properties like flexibility, rigidity, transparency and so on. Curing Speed and Depth: The focused laser in SLA allows for precise curing of thin layers, making it ideal for complex geometries but potentially slower in terms of overall build speed. Post-Processing: SLA parts often require post-processing steps like washing and post-curing to remove uncured resin and enhance material properties. Material Diversity: SLA materials include standard resins, flexible resins, tough resins, dental and biocompatible resins and specialised resins with varying mechanical, thermal and optical properties.	Mechanical Properties: The technology may influence the selection of resins with optimal mechanical properties for different applications. For example, DLP might be preferred for functional prototypes with high speed requirements. However, SLA may be a better option for highly detailed visual prototypes. Speed vs. Precision: faster build times in DLP might be preferred for projects with tight deadlines, while precision in SLA could be prioritised for intricate designs. Material Specialisation: Some manufacturers offer materials specifically tailored for each technology, considering the curing process and exposure methods that are unique to SLA and DLP. Application Specifics: Material selection depends on the intended applications. Biocompatibility, heat resistance, flexibility or optical clarity, which can influence the technology selection between SLA and DLP.
Digital light processing (DLP)	Parallel Exposure: DLP uses a digital light projector to expose an entire layer simultaneously, offering higher print speeds when compared to SLA. Resolution and Speed: Parallel exposure in DLP allows for quicker builds, making it well-suited for rapid prototyping and small-batch production. Material Properties: DLP often uses similar photopolymers as SLA despite a broader range of viscosities and formulations. Materials can be controlled for flexibility, strength, clarity and other attributes. Layer Thickness: Layer thickness in DLP can vary, thus impacting the resolution and smoothness of printed surfaces. Post-Processing: Post-processing for DLP-printed parts may also involve cleaning, curingand potentially additional steps, which depend on the material and desired properties. Material Availability: A variety of commercially available DLP resins offer different levels of durability, flexibility and aesthetics.	

Table 2. *Cont.*

VP Technique	Benefits	Impact on Material Choice
Continuous liquid interface production (CLIP)	Continuous Printing: CLIP utilises a continuous liquid interface to create objects by harnessing the interaction between UV light and a liquid photopolymer. This non-layered approach enables faster printing speeds when compared to traditional layer-by-layer methods. Print Speed and Consistency: Continuous printing in CLIP allows for rapid builds, making it suitable for both functional prototypes and production-grade parts. Dynamic Process: CLIP relies on a balance between UV light exposure and oxygen inhibition to control resin solidification, which is applicable to intricate geometries and smooth surface finish. Mechanical Properties: CLIP materials can be tuned for mechanical performance such as strength, toughnessand flexibility towards versatile applications. High-Resolution Capability: CLIP technology can achieve high resolution and details due to its continuous and precise printing process. Post-Processing: CLIP parts often require post-processing steps such as cleaning and post-curing to enhance material properties and remove uncured resin.	Speed and Precision: The continuous printing nature of CLIP is advantageous for projects requiring high-speed production without compromising the detail and precision. Mechanical Properties: Material selection can be made to meet specific mechanical requirements. CLIP resins can be optimised for stiffness, impact resistance and other performance related characteristics. Application Versatility: The ability of CLIP to achieve high resolution and diverse mechanical properties makes it suitable for a wide range of applications from consumer products to aerospace components. Post-Processing Considerations: The demand for post-processing, such as cleaning and curing, should be considered with respect to material selection. Resin formulations should allow for effective post-processing steps.

The choice between SLA and DLP technologies directly impacts material selection. Both technologies rely primarily on photopolymers, but their operational differences may cause diverse material requirements. The multifaceted consideration of speed, precision, mechanical properties and application demand determines the decision-making process, which ensures that selected materials are well aligned with desired strengths and noteworthy limitations in selected AM technologies. CLIP technology significantly influences material selection. Its continuous printing approach enables rapid builds with high resolution, which is suitable for various applications. Mechanical properties can be finely tuned through material selection to target versatile use across industries. The unique capabilities and merits of CLIP are usually affected by speed, precision, mechanical performance, applications, as well as material selection.

2.1. Case Study: Sinclairs Jewellers

Jewellery manufacture in Australia is an ideal candidate for AM technologies since the production is usually carried out in small batches with complex designs carried out by highly trained jewellers. The products are required to be highly personalised in design and development. The relative cost competitiveness of Australian manufacturing, when compared with the other top 25 exporting countries, declined by over 15% over a decade from 2004 to 2014 according to a study from The Boston Consulting Group [24]. A large part of the production cost of jewellery is labour, which rose 48% in Australia over the report timeframe. By reducing the number of highly trained jewellers, Sinclairs Jewellers in Applecross, Western Australia, could save over 25% of their operating costs by incorporating AM as part of their production process [29]. The United States has the largest jewellery market so far, and it can manufacture goods that are 30% cheaper than those produced in Australia [24]. Hence, any cost reduction for manufacturing companies in Australia makes them more competitive in the global marketplace.

Sinclairs Jewellers uses specialised AM-based resins and two DLP Asiga MAX machines, as seen in Figure 7, to make 3D-printed designs in order to replace wax moulds in a lost-wax casting process. To achieve a high-resolution print, Asiga SuperCAST X and SuperCAST HD are used with the printer. These newer resins allow for an ash-free burnout during casting. Burnout is referred to as the resin encased in ceramic investment powders, which is put in a kiln and heated to a certain elevated temperature, and eventually turns to ash and burns out of the mould. The printers and the resins have allowed for faster production time with reduced labour costs. They can provide customised client interactions to create bespoke jewellery while maintaining quality control as everything is produced on the premises from alloying to manufacture. Substandard castings can be rectified immediately since all are in-house performed, thus creating a faster turnaround for clients. Figure 8 shows Sinclairs Jewellers process for manufacture, where jewellers are only necessary for the phases of sprueing, clean-up and stone setting.

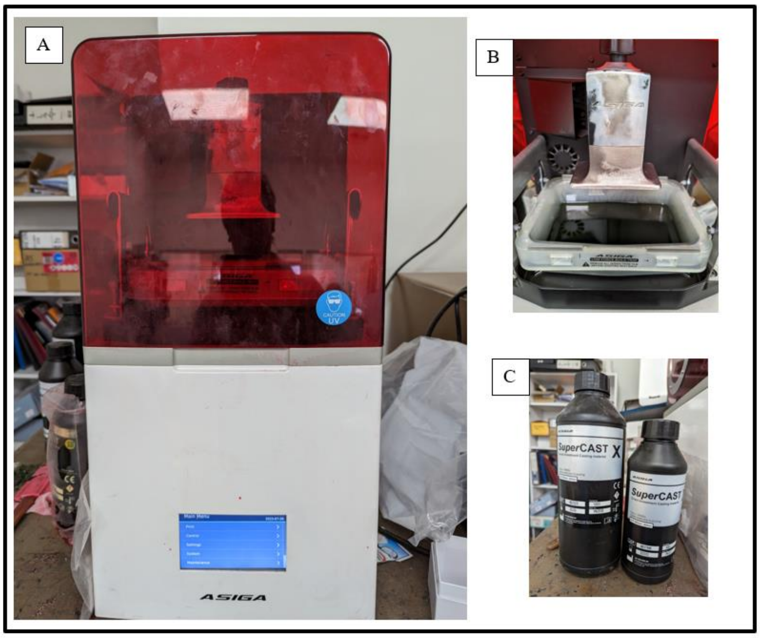

Figure 7. (**A**) Asiga MAX DLP printer (printing resolution: 62 µm). It uses a 385 nm (high-power UV LED) or 405 nm wavelength to cure the resin. (**B**) Inside the build chamber of the Asiga MAX printer, which shows the build tray full of resin ready to print. (**C**) Asiga SuperCAST X resin used for 3D model manufacture.

The problems during the initial use of resin models to be mentioned are poor surface finish and porosity. The first aspect causing poor surface finish is spalling. Spalling occurs when minute ceramic parts from the gypsum investment material break off and fall into the mould during the burnout process, which are embedded in the metal during the casting process. These ceramic parts are then removed from the piece by a laser during the finishing process. The part often has to be scrapped as the surface finish is unrepairable, adding extra time and cost to the piece. To eliminate spalling, a phosphate-bonded investment material can be used. Investment material is a mixture of a bonding agent made from gypsum or silica and a refractory material to generate a ceramic when combined [33]. A gypsum-based bonding agent is generally employed in a low-temperature range of 450–700 °C for investment casting. In contrast, a phosphate-based bonding agent is generally utilised for higher temperatures in range of 650–760 °C [35]. Phosphate investment material casts can be seen in Figure 9 after they go through a burnout cycle to remove the resin and harden the mould. Once this change is made, there are no further issues with spalling.

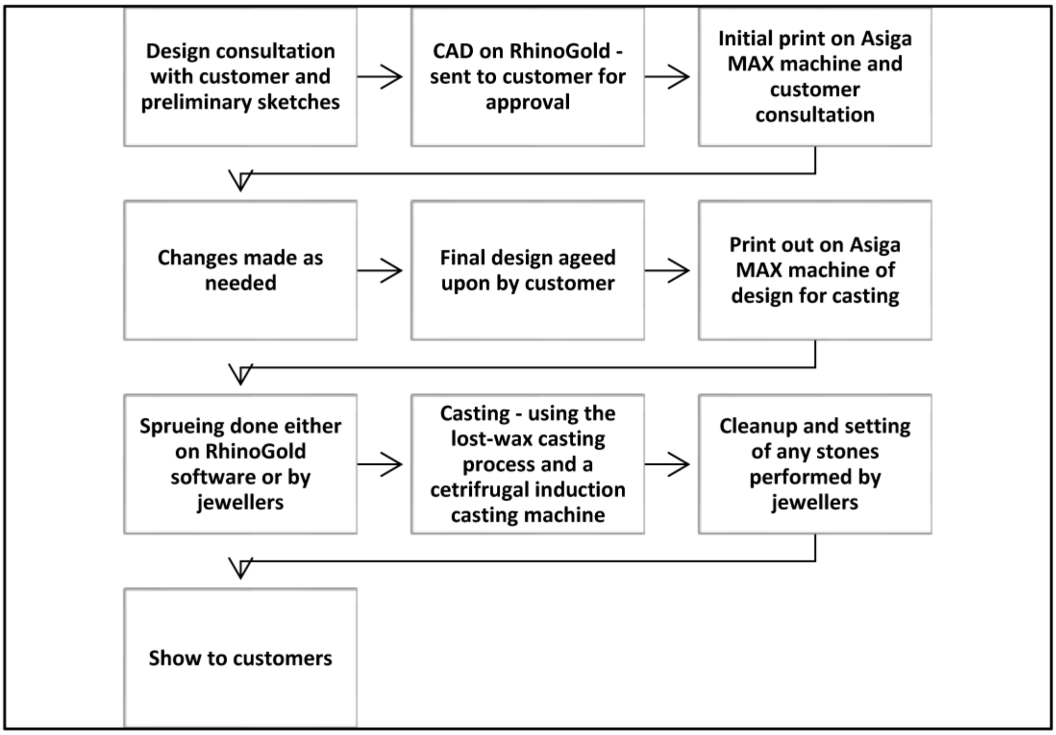

Figure 8. Sinclairs Jewellers process for creating personalised customer jewellery using AM. Design costs were greatly reduced due to the ease of producing life-like renders on RhinoGold, which also made design changes quicker due to the built-in features in the CAD programme. Jewellers are required for the clean-up and stone-setting phases.

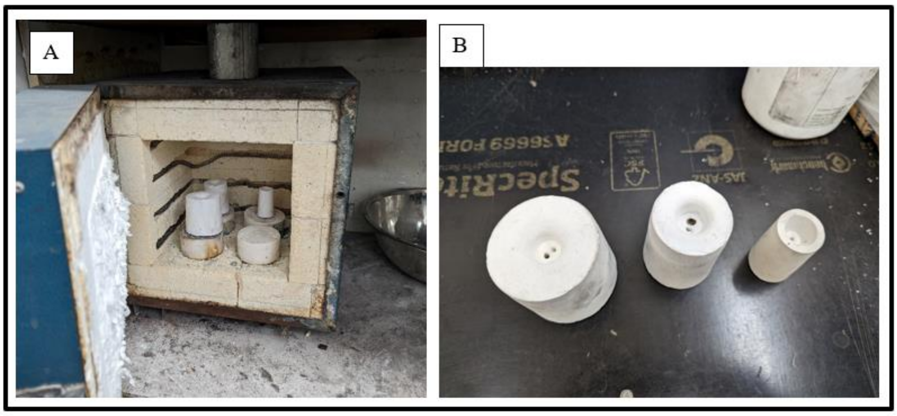

Figure 9. (**A**,**B**) Phosphate investment casts in the kiln after burnout. Asiga resins have a burnout schedule of 149 °C for 2 h, 371 °C for 2 h and 482 °C for 2 h, and then remain at 750 °C for 4 h. Then moulds are reduced to the cast temperature for 2 h and get ready to go to a centrifugal induction casting machine.

The porosity is caused by small holes detected in cast metals due to voids or small holes called pores [36]. Initially, Sinclairs Jewellers had many of their casts suffering from porosity; Table 3 outlines the causes of porosity and the ways in which Sinclairs overcame these problems with full AM adoption.

Table 3. Causes of porosity [34] and resolutions identified by Sinclairs Jewellers.

Cause	Resolution
Alloy composition causing the vaporisation of low melting temperature metals.	Used only their own alloy combinations: For gold alloys—Au, Ag, Pd, and a Cu/Zn mixture, and for palladium alloys—only Pt and Co.
The location and size of the sprues cause the metal to flow irregularly. An insufficient amount of metal for the cast, causing back pressure to be insufficient. Uneven cooling of the cast, resulting in shrinkage.	A combination of jeweller expertise and iterative procedures.
Flux is present in large amounts, causing gas bubbles to form. "Pinhole porosity" is caused by trapped gas in the cast.	Metal is melted and cast in an argon gas atmosphere using a carbon crucible to reduce the amount of flux required and diminish "pinhole porosity".
The use of an oxidising or high air pressure flame during the melting of the metal adds oxygen into the alloy.	An induction coil melts the metal alloy in an argon gas atmosphere to stop the incorporation of oxygen into the cast.
Incomplete burnout of the resin, leaving ash residues.	A specialised kiln burnout is controlled by a computer programme to ensure correct burnout time for the resin and alloy being used.

2.2. Industrial Challenges with Current Manufacture Using VP Technique

One of main drawbacks of using printable photoresins is their inferior mechanical properties compared to other manufacturing processes widely used in industries such as milling, extrusion and injection moulding [1]. Additionally, relative to other thermally cured materials, their glass transition temperature (T_g) and toughness are major hurdles to overcome, which can cause the layers to fail to bind together or cause cracking [37]. The T_g of resins is the temperature at which they transform from a brittle, highly ordered and rigid state to a state where they can flow or deform under shear stress [2]. The glass transition of a particular resin affects the temperature of the build chamber since the resin should flow and cure properly without causing failed prints. Curing and annealing the printed products are also affected by T_g mainly because correct processes and temperatures must be used for stress relief and dimensional stability [2]. The thermal expansion and contraction behaviour of resins can be affected by the variation of temperature. As such, precise knowledge of resin properties needs to be known to warrant dimensional accuracy [37].

The success in improving the tensile strength of 100 MPa and heat deflection temperature of 191 °C at 1.82 MPa has been noted with cyanate ester monomers despite the drawback of being toxic to humans before and after being photocured [17]. However, cyanite esters exhibit the properties of 15% glass-filled nylon such as increased strength and stiffness, improved dimensional stability, enhanced wear resistance, high impact strength and chemical resistance. It is a lightweight material and a very commonly used nylon for helmets, gear and engine parts, as well as in the aerospace industry [38]. Epoxy resins have also been developed with a high tensile strength of 88 MPa and a heat deflection temperature of up to 131°C at 1.82 MPa notwithstanding their high moisture sensitivity and low printing speed [17]. As such, acrylate prepolymers are commonly employed for photo-curable AM because of their ability for easy photopolymerisation with a shorter curing time. They can reach a tensile strength of approximately 50 MPa and a heat deflection temperature of 130 °C at 1.8 MPa. However, these properties vary greatly due to the use of additives to improve desired resin properties [17]. Some additives can increase resin viscosity, while uncured printable resins are generally restricted to a viscosity of 5000 cP, and the viscosities of high-speed printable resins usually appear to be lower than 1000 cP [1,17,39].

The separation force of higher-viscosity resins causes several issues with respect to printing [17]. Various methods have been implemented to print more viscous resins such as heating the resin during photopolymerisation [3]. However, this is unsuitable for all resins because some resins undergo thermal polymerisation, and toxic chemicals from the (meth)acrylate formulations can be hazardous to workers [17]. Moreover, Liu et al. [39] demonstrates that low-viscosity resins can be created using low-viscosity reactive diluents. More research should be conducted to be well aligned with industrial uses and in-field applications [13].

Overall, the challenges associated with current VP techniques for industrial manufacturing using printable photoresins are multifaceted and encompass various mechanical and thermal limitations. Notably, the mechanical properties of such resins are inferior to those of conventional manufacturing processes such as milling, extrusion and injection moulding. Their T_g and toughness undergo significant obstacles, potentially leading to layer delamination, cracking and compromised dimensional accuracy. In particular, T_g directly affects the build chamber temperature and influences curing and annealing processes, which are crucial for stress relief and dimensional stability. Thermal expansion and contraction behaviour further complicate the acquisition of precise dimensional accuracy. Noteworthy advancements have been made such as higher tensile strength and heat deflection temperatures through cyanate ester monomers despite their inherent toxicity. Epoxy resins, notwithstanding their high tensile strength, can be hampered by their sensitivity to the moisture and low printing speed. Acrylate prepolymers, on the other hand, possess moderate tensile strength and heat deflection temperature, which are prone to the variability due to the use of additives. The challenges encountered by higher-viscosity resins lead to innovative approaches like heating during photopolymerisation or the development of low-viscosity reactive diluents. However, special caution must be taken with toxic chemical hazards in good alignment with industrial applications. In short, these challenges are required to be overcome with interdisciplinary research efforts that can bridge the gap between resin formulation, improvement of mechanical properties and a precise control of printing processes, which ultimately enables the integration of VP techniques into mainstream industrial practices.

3. Hybrid AM

Hybrid manufacturing (HM) is an advanced approach that AM and subtractive manufacturing (SM) techniques in a single integrated process [40]. By fusing the strengths of both additive and subtractive processes, hybrid manufacturing attempts to overcome the limitations of each method individually while maximising their benefits [40]. In an HM setup, additive and subtractive operations are seamlessly integrated, and are often within the same machine or workstation. The process begins with AM where a 3D printer deposits material layer by layer to build up an initial structure. Once the additive phase is complete, SM techniques like computer numerical control (CNC), milling or precision machining are used to refine part geometry, achieve tight tolerances and add fine details. HM can reduce material waste by adding material only to appropriate areas and then removing excessive amounts of material through subtractive operations [41]. The combination of additive and subtractive processes enables the creation of intricate geometries through AM techniques, which are followed by precise subtractive operations to achieve high tolerances and smooth surface finish. The additive phase can use a variety of materials, including specialised alloys and composites, while the subtractive phase can rely on conventional machining tools for optimal material removal. HM enables the creation of parts with internal structures, channels and voids that might be challenging to achieve via solely subtractive techniques. This accelerates the production of complex parts by leveraging the speed of AM and the precision of subtractive methods in a single workflow. Such advantages are summarised in detail in Figure 10.

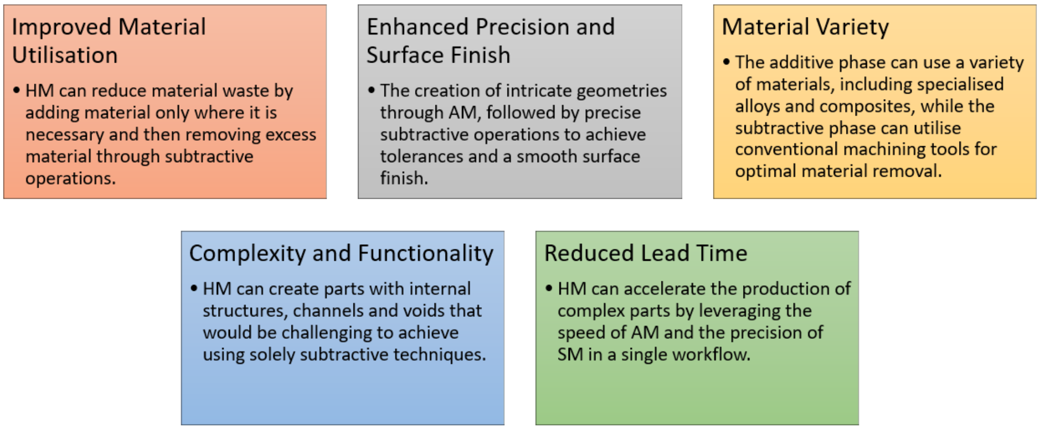

Figure 10. Advantages of hybrid AM [38].

HM is used in aerospace to create complex components with optimised geometries, reduced weight and improved structural integrity [39]. It is particularly valuable for creating engine components and airframe parts. Moreover, it can produce patient-specific implants and prosthetics with precisely tailored geometries in the medical field [38]. The additive phase can incorporate porous structures for the enhancement of osseointegration (i.e., the process of natural bone fusing and integrating with an artificial implant such as a prosthetic limb or dental implants for stability and functionality), notwithstanding proper fit warranted by subtractive operations [39]. HM is used to create injection moulds, die-casting moulds and tooling components with intricate features, along with reducing tooling lead time and improving production efficiency. The automotive industry employs this method to create lightweight and complex parts such as engine components, transmission components and customised vehicle parts. In energy sectors, it contributes to producing complex turbine components, enhancing efficiency and reducing maintenance requirements. HM can also be used in jewellery design and artistic creation to achieve intricate designs with high precision and surface finish. It further accelerates the prototyping process by combining the speed of AM with the precision of subtractive processes.

4. Environmentally Friendly Additive Manufacturing

The state of environmentally friendly AM stands as a pivotal turning point, catalysing a shift towards sustainable practices within manufacturing industries [4]. As environmental impact and resource conservation are of a great concern, the adoption of sustainable and ecologically available polymers emerges as a transformative trend that is poised to reshape the future of AM technologies. The primary goal is to curtail waste generation while optimising the use of natural resources and propelling industries towards a greener and more sustainable future [1,4].

AM is the seamless integration of three key factors when considering the widespread embrace of environmental friendliness, namely component properties, manufacturing speed and cost-effectiveness [13]. More companies are increasingly recognising that the allure of environmentally friendly materials must be coupled with the ability to match or surpass the attributes of their conventional counterparts. The realisation that these eco-friendly practices can coexist with competitive manufacturing speed and cost efficiency becomes a crucial factor for driving the transition towards more sustainable production methods.

Traditional AM technologies relying on polymer-based materials derived from epoxides or acrylates inadvertently contribute to a substantial carbon footprint due to their origins as by-products of fossil fuels [42]. Furthermore, these materials tend to be transformed into thermosets upon photopolymerisation, making their environmental implications more pronounced [4]. To address this, numerous studies have been dedicated to exploring alternatives to these fossil-based acrylates and epoxides. A promising avenue involves the utilisation of photopolymers crafted from renewable resources like starch, lignin and vegetable oils. By leveraging these sustainable sources, the industry endeavours to diminish its dependence on fossil fuels while simultaneously reducing its carbon footprint.

Biobased, biodegradable and recyclable materials are deemed the key to the innovation of environmentally friendly AM, dismantling the barriers to large-scale adoption [4]. The transition from conventional materials to these sustainable alternatives requires a holistic approach, not just within material formulation but also across the entire AM ecosystem. These materials provide the promise of significantly mitigating environmental harm, fostering a circular economy wherein end-of-life products can be reused, regenerated, or reintegrated into a production cycle [14,42].

Highlighted in the spectrum of research endeavours is a diverse range of biobased and sustainable photopolymers, which underscores the remarkable breadth of applications encompassed by these innovations. As indicated by the diverse examples showcased in Table 4, environmentally friendly materials are making inroads into industries spanning healthcare, consumer goods, architecture and beyond. This reveals the versatility of such materials and their potential to revolutionise various sectors, in good alignment with the global aspiration for greener and more sustainable production practices.

Table 4. Natural polymers used for AM [14,38].

Alginate-Based Resins [43]	Alginate, derived from seaweed, is a naturally occurring polysaccharide. Alginate-based resins are biocompatible and biodegradable. They are used in bioprinting and tissue engineering applications due to their ability to support cell growth and mimic biological environments with widespread applications in wound healing, tissue engineering and drug delivery.
Cellulose-Based Resins [44,45]	Cellulose is the main structural component of plant cell walls. Cellulose-based resins are renewable and biodegradable. They can be used to create sustainable and biocompatible materials for various applications such as packaging, biocomposite reinforcement and biomedical devices.
Chitin-Based Resins [42]	Chitin is a natural polymer discovered in the shells of crustaceans and insects. Chitin-based resins are biodegradable and possess antimicrobial properties. They can be used in wound healing materials and environmental applications.
Hyaluronate-Based Resins [46]	Hyaluronate (hyaluronic acid) is a polysaccharide found in connective tissues. Hyaluronate-based resins are biocompatible, which are used particularly in medical applications such as drug delivery and tissue engineering due to their ability to promote cell adhesion and growth. They are commonly used for bio-inks as a typical example.
Poly (3-Hydroxyalkonate) Resins [46]	Poly(3-hydroxyalkonate) is a biopolymer produced by microorganisms. These resins are biodegradable with a major focus on various applications including packaging, bone scaffolding and tissue engineering.
Polysaccharide-Based Resins [47,48]	Polysaccharides such as starch, cellulose and chitosan can be used to create sustainable photopolymers. Polysaccharide-based resins are renewable and biodegradable and can be modified to achieve specific properties for different applications such as material packaging.
Protein-Derived Resins [49–51]	Proteins extracted from natural sources can be used to create photopolymers. Protein-derived resins can offer biocompatibility and the potential to create biomimetic materials for tissue engineering and medical applications.

Table 4. *Cont.*

Starch-Derived Resins [52,53]	Starch, a carbohydrate derived from crops like corn or potatoes, can be modified to create resins. Starch-derived resins are renewable and biodegradable. They can be used in packaging, coatings and other applications with the priority of sustainability.
Isocyanate Functional Groups and Polyol Groups [18]	Isocyanate groups (NCO) are reactive functional groups found in compounds like diisocyanates. They can react with polyols to form polyurethane materials. Polyols are compounds with multiple hydroxyl (-OH) groups. When they react with isocyanates, they form polyurethane. Isocyanate-functional and polyol-based resins are commonly used in polyurethane materials. They yield a wide range of mechanical properties including flexibility, toughness and hardness. However, careful handling is essential due to the potential health and environmental concerns associated with isocyanates.

In manufacturing processes that rely on lost wax casting processes like jewellery manufacturing, many resin parts are produced before the final part is burned out in the kiln. Recycling these resins is challenging due to their chemical structures, making reusing or recycling difficult or impractical. Chemical recycling, where cured resins are broken down into constituent molecules for reuse purposes, is not widely available with a high cost [4]. Mechanical recycling means that the thermoplastics are ground into powders and further blended into other thermoplastic materials to create an end-use product [4]. Collection programmes from material manufacturers have been started to promote responsible waste management in the industry such as services offered by Re-Cycleo by Sculpteo and Precious Plastic in possession of global and local collection facilities [54,55].

5. Multi-Material Additive Manufacturing

AM has focused on using single materials but starts to embrace the advantages of combining and using multi-material functionality [56]. AM has yet to be directed in many industries and specific applications due to the design limitations of single materials [13,57]. An example of multi-material use is hard-soft composites created for aerospace and robotics industries called functionally graded materials (FGMs), which are special materials with a smooth interface continuously from one surface to another [58]. Mirzaali et al. [58] also stated that printed FGMs are superior to conventional composites because the delamination can be halted due to the engineered function gradient at their hard-soft interfaces.

With the various uses of multi-materials, over 200 research articles have been published in the last six years on energy harvesting, aerospace applications, soft robotics and soft sensors [53]. Manufacturers can use multi-materials to make customisable materials with selected performance criteria [56]. Researchers have identified several potential applications for multi-material additive manufacture (MMAM). Aerospace applications include components with integrated electronics or sensors with embedded functionalities that will reduce the weight of a component [57]. Medical applications include personalised implants and drug delivery systems that consider the biological needs of patients [48,57]. Consumer goods can be customised like footwear with different stiffness and flexibility zones. The manufacture of jewellery can be personalised and incorporate a variety of metals in different zones of the part for aesthetic reasons, design functionality such as increased strength, as well as cost reduction in the manufacturing process.

The benefits of using MMAM include design flexibility, reduced assembly time, waste reduction, enhanced functionality and cost-effective prototyping [59,60]. MAMM can produce an intricate design using an FGM that would be impossible to achieve through traditional manufacturing methods [61]. The combination of multi-materials simultaneously eliminates part assembly while saving time and labour costs by only using the material required during printing. MAMM enables to incorporate conducting, insulative or flexible materials in order to form a print for increasing the functionality of parts [60].

Significant challenges arising from combining materials in MMAM include the differences in the coefficients leading to residual and surface stresses in the components, to which metallic MMAM is particularly susceptible [61]. Material selection design is an option for future research, which focuses on defect reduction in industrial applications and the yield of an optimal distribution of the materials by understanding how the composition of these materials affects interfacial bonding, cracking mechanisms and reaction kinetics [56,59]. Design protocols can be built into this research to ensure design-related concerns are well addressed such as poor scalability and surface finish issues. More research should be undertaken to incorporate functionally graded additive manufacturing (FGAM) protocols into all types of MMAM [60].

Low production throughput can also be attributed to the complexity of MMAM because the process of changing materials includes more than just changing a print cartridge, printing parameters or nozzles [61]. The chemical compositions of the materials being used and their constraints allow the users to have extensive knowledge of the materials as to how they will act when bonded [60]. More research needs to be conducted into material compatibility though no practical industrial guidelines are available to help engineers choose proper materials or evaluate the printability of such materials [61]. Many of the studies analysed by Nazir et al. [56] showed that much of the research that has been conducted on MMAM aimed at investigating the mechanical properties of multi-material components. However, less than 17% included the numerical prediction via finite element analysis (FEA) against their empirical results, making the material comparison unsuitable This is especially the case for those based on elastomers and hydrogels. Further study on tensile, chemical, fatigue and impact properties is required with a standardised approach to evaluate these properties holistically.

Steuben et al. [61] addressed tool paths or "slicing" software development that improved mechanical properties of components and their design intent by using multi-materials. It also highlights the necessity of involving more research on designing MMAM components based on different AM processes. The post-processing of such components should be developed since current post-processing only focuses on homogenous materials [58]. Zheng et al. [57] have found that despite much MMAM-related research reported, there is a high demand for more investigations into developing its advanced technologies. This includes more research for industry-specific applications concerning thermal, biocompatible and electrical properties, fire resistance, as well as 4D printing. Ge et al. [62] and Nugroho et al. [18] have identified 4D printing as an advanced manufacturing method for producing parts that can adopt new shapes or functionality after material fabrication. These intelligent or living structures can change the shape or function when exposed to particular stimuli such as heat, light or electrical impulses [63]. In the last six years, AM using multi-materials has been an emerging technology in a focus of future research endeavours.

6. Future Perspectives

In the realm of AM technologies, innovative techniques such as bottom-up manufacturing through VP have gained substantial attention for their potential to revolutionise traditional manufacturing practices. This approach offers multiple advantages including high-resolution printing, reduced material waste and accelerated printing time. Nonetheless, challenges inherent to VP have been encountered, necessitating in-depth exploration and resolution. The phenomenon known as separation force, arising from the detachment of cured parts from the printing platform, poses significant reliability concerns, which further leads to the deformation of final products. To alleviate this, a judicious selection of materials for the release liner becomes imperative. Additionally, the quest for higher printing speed remains a pivotal pursuit for the further integration of AM technologies within manufacturing industries. Advanced techniques such as adaptive layering, topology optimisation and machine learning programmes have been harnessed to optimise printing time and material use. Nevertheless, a comprehensive investigation into material diversity, scalability, resolution, post-processing and application-specific research remains pivotal to push the boundaries of rapid production in AM. The evolution of post-processing techniques to be aligned with novel resins and material combinations, alongside the challenges of integrating biodegradable and recyclable resins, underscores the ongoing dynamism in this field. With the increasing complexity of multi-material printing, complicated material selection, adhesion, compatibility and a control of residual stress should be seriously taken into account. This paper delves into these intricacies, seeking to elucidate the multifaceted landscape of challenges and opportunities in VP-based AM for future manufacturing endeavours.

Bottom-up manufacturing in VP allows for high-resolution printing, less material waste and faster printing time [64]. However, this can cause a large force to be created by the cured parts attached to the printing platform lifting from the release liner, which is known as the separation force [64]. The force can cause reliability issues in the build and deformation of final products [38]. New materials for the release liner must be selected appropriately in order to reduce the contact force.

Higher printing speeds should always be improved so AM can be further utilised by the manufacturing industry [1,13]. Optimised programmes and machine learning programmes can increase print speed [65]. Adaptive layering is where programmes can determine the parts of the build that do not require high resolution and thus increase layer height and wall thickness. It enables us to reduce the number of layers required and print time. Topology optimisation (TO) and hybrid analytical thermal topology optimisation (HATTO) of cermet composites and multi-material printed components have been implemented to optimise specific properties such as maximising stiffness while minimising stress concentration, as well as material usage and weight [66–69]. Material properties and design constraints are considered, and optimal material distribution is also identified [69]. TO can create infill structures or lattices to reduce the material required while maintaining the strength of the parts. TO can also help with the ideal placement and size of support structures to print overhangs or complex geometries in order to reduce material usage and increase print speed. More efficient paths can be created, and printing parameter profiles can thus be saved for the manufacture of common parts [1].

CLIP and high-area rapid printing (HARP) have improved printing speeds [10]. However, further research in this area must be conducted on material diversity, scaling and resolution, post-processing and surface finish, design guidelines and application-specific research [68]. Higher printing speed will assist in large-scale production for manufacturers. Nonetheless, larger machines with greater resolution must be developed to print large objects faster in a similar manner to HARP [69]. Concentrated suspensions of resins with metallic or ceramic additives can still be time-consuming owing to liquid viscosity and flow rate [1].

Many post-processing techniques have been devised to characterise mechanical properties of cured resin [3]. Nonetheless, many novel resins are being investigated with different post-processing requirements [1]. Mechanical properties can be significantly tailored through post-processing techniques such as heat treatment to relieve internal stresses, annealing to increase density by reducing porosity and increasing crystallinity, post-curing to increase crosslinking density for higher strength, and proper cleaning of the parts in order to achieve consistent material properties [2]. As new techniques and materials become available, specific investigations on the best post-processing techniques would be essential for a holistic AM process [28].

The mechanical properties of biodegradable and recyclable resins are a challenge for future research where biobased additives are used in current resins to improve their properties [4]. Covalent adaptable networks (CANs) are polymeric materials that can mimic thermosets and thermoplastics. Dynamic crosslinks turn the materials into a strong network of polymers and malleable plastics under heat or light stimuli. As such, complete degradability has yet to be reported [4]. The printability of environmentally friendly materials with comparable properties to traditional manufactured products has not been fully explored [44].

Material selection, design and manufacturing aspects remain at the forefront of research carried out in the multi-material arena [58]. Multi-materials that exhibit high functionality with complex geometries to mimic natural materials that can be printed with existing technologies will assist in the AM uptake in industries due to its highly customisable ability [56,64]. Multi-material adhesion and material compatibility using standardised experimental designs for material comparison is a new area yet to be studied [58]. Many novel multi-materials being researched have not encountered complex analyses of their properties such as chemical reactivity, fatigue and impact testing [61]. Widely available computer programmes to design material gradients and the optimal distribution of materials for multi-material parts ultimately reduce this time-consuming process [60].

The reduction of residual and surface stress at interfacial boundaries with the correct combination of materials, especially those with different coefficients, is a broad area of study since there are no standards currently in place to help engineers assess the combinations of materials [61,65]. Multi-materials used for structural purposes still need further research because low production throughput, poor scalability and surface finish issues remain major obstacles [65].

Post-processing is currently tailored towards single-material printing. New post-processing techniques must be developed for the range of available multi-materials [61]. Cross-contamination and low print speeds due to the change of materials may become a future hot area for further study [61,65].

7. Summary

AM is one of main forces in new industrial revolution, giving designers and engineers flexibility and design control. It can help businesses reduce costs when producing small lots where customisation is important. This research can then be communicated to engineers in manufacturing roles so they can choose the correct methods and materials.

In the pursuit of advancing AM technologies via VP technique, the complexities and potential breakthroughs inherent to this paradigm have been unveiled. Advancements and challenges in AM and MMAM via VP are summarised in the following:

- There is a critical hurdle posed by the separation force of models with the vat, requiring a careful selection of durable release liner materials;
- The research community needs to mitigate reliability issues and deformations in printed products for higher reliability;
- An emphasis should be laid on enhancing printing speeds through techniques like adaptive layering, topology optimisation and machine learning algorithms. There is an essential role for continued research in making AM technologies viable for more manufacturers and large-scale production;
- More work should focus on a major thrust for efficient large-scale production via increased printing speed;
- The persistence of the demand for larger machines with higher resolution is necessary despite the improvement in printing speed;
- There is a dynamic post-processing landscape involving diverse resins and materials, especially MMAM. Special attention should be given to post-processing in light of new printable materials;
- Continuous exploration of tailored techniques for integrating advanced materials into AM processes;
- The incorporation of biodegradable and recyclable resins and the challenges of multi-material printing underscore the long-term demand for ongoing research;
- More exploration of resin toughening and modification through additives and novel chemistries is required in future research endeavour;
- The selection of optimal materials, residual stress mitigation, and tailored post-processing techniques emerge as critical pathways for technological advancement;

- Interdisciplinary research and collaboration eventually lead to better understanding and feasible solutions to current challenges encountered in AM technologies, especially in the Australian market.

This review has identified several knowledge gaps in current research for VP and MMAM. Ongoing research must focus on continuously increasing print speed while maintaining high resolution. Moreover, larger printers should be made since larger components begin to be manufactured with faster print speeds. Resin toughening and modification through additives and novel chemistries need to be developed, while environmentally friendly solutions for these chemistries are highly sought. Researchers and companies need to investigate post-processing techniques to enhance resin properties and improve surface finish, especially with the development of new printable materials. In this growing industry, more research is essential for the viability of AM to reach more manufacturers and produce much larger production runs.

Many small and medium enterprises in Australia have begun to incorporate AM into their manufacturing processes. Supply-chain disruptions have impacted roughly one third of all Australian businesses during and after the COVID pandemic according to D'Souza [70], with 80% of those businesses not receiving goods from their suppliers. Future development of automation and hybrid printing options will allow companies to further embrace this technology. Jewellery manufacturers are uniquely positioned to embrace this technology as their businesses are centred around highly customisable, unique products that require large amounts of skilled labour time. Costs and time of manufacture can be reduced by implementing AM techniques, thus increasing their competitiveness in the worldwide jewellery market. However, AM in various Australian sectors can be incorporated into widespread applications as follows:

- Environmental conservation using biodegradable 3D-printed structures [71]: Researchers in Australia have been testing biodegradable 3D-printed structures to protect budding wetland species and slow coastal erosion. These structures are made from potato starch and are designed to biodegrade within two to ten years, ensuring minimal environmental impact. This initiative is part of the "Regenerating Our Coasts" programme, which aims to monitor the survival and growth of mangroves planted in these structures. The project is a collaboration involving Deakin University's Blue Carbon Lab, which is supported by Beach Energy. Citizen scientists are actively involved in collecting data to monitor the seeds and measure their survival and growth;
- Innovation in AM with post-processing technology at Australia's Nuclear Science and Technology Organisation (ANSTO) [72]: An Australian company has made significant strides in AM by utilising a post-processing technology for titanium at ANSTO. This innovation enhances the material properties and performance of 3D-printed components;
- Largest 3D printing machine being used in Australia to increase job growth in the caravan industry [73]: A Queensland caravan company has integrated the use of the largest 3D printing machine in Australia to manufacture caravan components in order to reduce cost and keep lightweight structures or parts for towing reasons.

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