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# Research progress in multi-material laser-powder bed fusion additive manufacturing: A review of the state-of-the-art techniques for depositing multiple powders with spatial selectivity in a single layer

*Andre Mussatto*[1, a]

[1] School of Mechanical and Manufacturing Engineering, Dublin City University, Glasnevin, Ireland

[a] Corresponding author: andre.mussatto2@mail.dcu.ie

## Highlights

- The latest developments in multi-powder delivery systems for laser-powder bed fusion is presented.
- Multi-material laser-powder bed fusion is a disruptive technological innovation to its parent single-material processing.
- Precise and accurate depositions of small amounts of powders for the formation multi-material intra-layers is essential in the modern production paradigm.
- In line with the fast development of laser-powder bed fusion, further developments and new concepts for multi-material processing, adapted to industry-specific requirements are expected.

## Abstract

Additive manufacturing offers great potential and versatility for manufacturing high-quality and geometrically complex components. Multi-material laser-powder bed fusion is an emerging additive manufacturing approach where multiple materials are combined in order to manufacture multi-material components with new possibilities in product design and spatially tailored properties. Several multi-material delivery systems have been developed and a broad spectrum of applications have been demonstrated using multi-material laser-powder bed fusion. This work provides an overview in terms of architecture, construction and applications of all existing multi-material delivery systems developed for multi-material laser-powder bed fusion. Numerous challenges related to the deposition and processing of multi-materials which have been reported are discussed and potentials, which emerged through the use of multi-material laser-powder bed fusion are discussed together with the future perspectives.

**Keywords:** multi-material printing; functionally graded materials; alloying; additive manufacturing; laser-powder bed fusion

## 1. Introduction

Several additive manufacturing technologies are employed in industrial manufacturing nowadays. For instance, laser-powder bed fusion of metals is utilised for serial production in aerospace, biomedical and automotive industries [1–3]. This is mainly because the additive manufacturing technologies bring forward inherent flexibility and efficiency in producing highly complex components [4]. However, most of the additive manufacturing systems have been designed to print components from a single material [5,6]. This is especially true with regards to the laser-powder bed fusion systems [7]. Multi-material laser-powder bed fusion provides a unique capability for the manufacturing of even more complex components where complementary functionality is realised using differences in material properties [8]. This means that throughout a single component, properties like mechanical, thermal and electrical, can be defined in areas that require it the most. Therefore, the multi-material laser-powder bed fusion technology can enhance the performance of components by varying material compositions and or material types. In fact, it is seen entailing an emerging direction and a range of opportunities for design, functionality, and cost-effective high-value components.

Although there is a variety of commercially available laser-powder bed fusion systems, only a limited number are designed for the production of components with multiple materials [9–12]. Also, as multi-material laser-powder bed fusion is relatively new, the powder deposition architecture of commercially available systems is constantly being redeveloped. As a result, multi-material processing in laser-powder bed fusion is a relatively less explored field. Therefore, this article presents an overview of the recent research progress in multi-material laser-powder bed fusion, including technical and scientific challenges, opportunities and future perspectives.

## 2. Latest Developments in Multi-Powder Delivery Systems

### 2.1 Conventional Powder Deposition

Conventional laser-powder bed fusion systems are suitable for the creation of composites and alloys *in situ* through the use of elemental powder blends [13–15]. These laser-powder bed fusion systems can also be used for multi-material printing. However, they only allow the use of a single material at a time and for layered material transitions. Therefore, the printing of multi-material components with conventional laser-powder bed fusion systems can be divided into three main steps: (1) pausing the building process at the layer where the material transition is desired, (2) changing of powder and (3) resuming the building process. To avoid a large volume of powder contamination at the end of the building process, the previously used powder is removed at step (2) [16]. Also, to mitigate oxidation of the printed surfaces, the printer chamber is preferably maintained flooded with the inert gas and the building process then can be resumed once the oxygen level has reached the specified threshold [17]. Another recommendation at step (2) is to apply several passages of the recoating unit to assure sufficient compaction of the powder and that the powder bed is levelled with the height of the last printed layer [18]. Additionally, at step (3) it is recommended to repeat the lasing on the transition layer 2-3 times to promote a better fusion between the materials [17]. Figure 1 illustrates examples of multi-material components printed by using conventional laser-powder bed fusion systems.

(a)
(b)
(c)

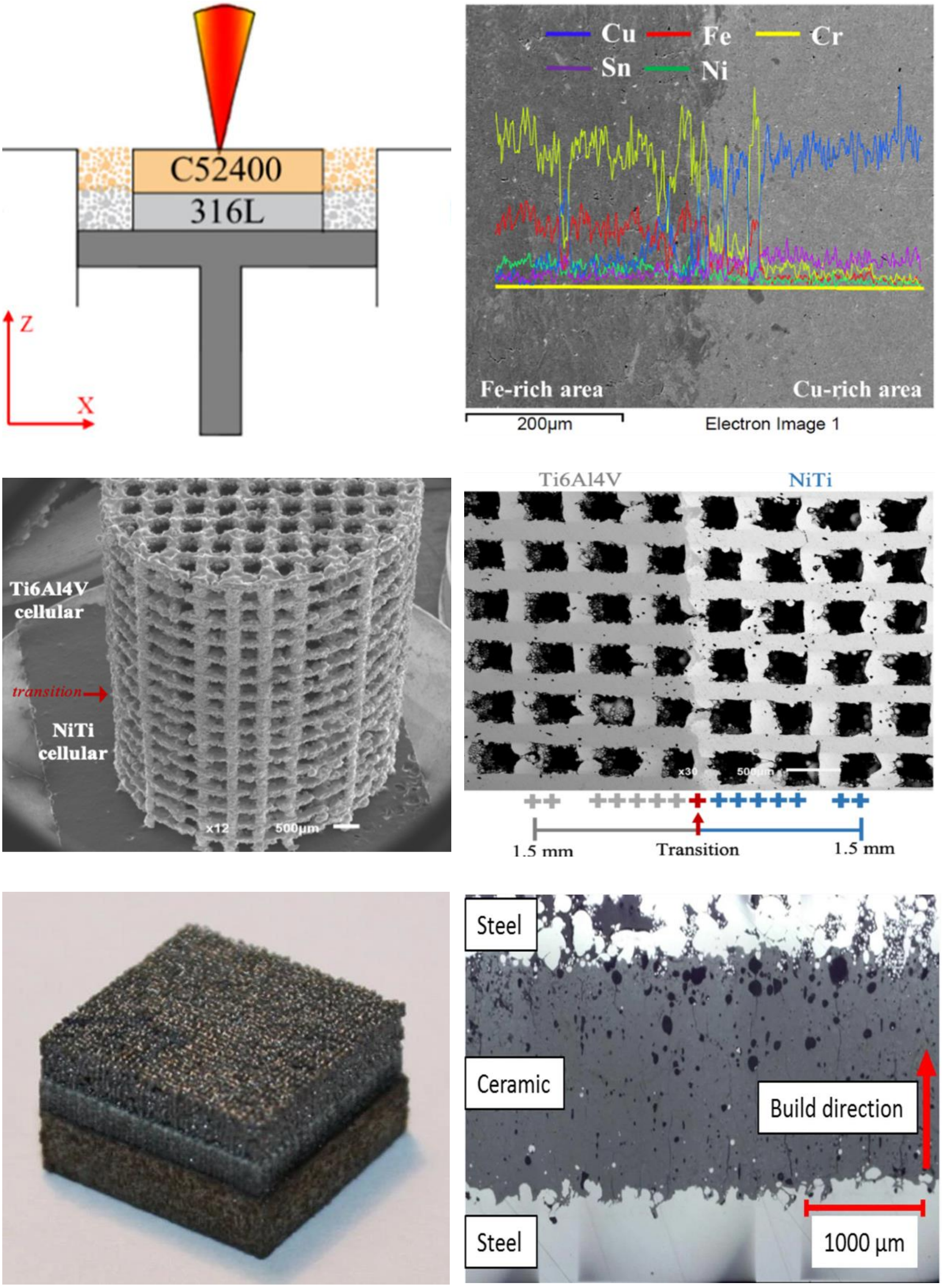
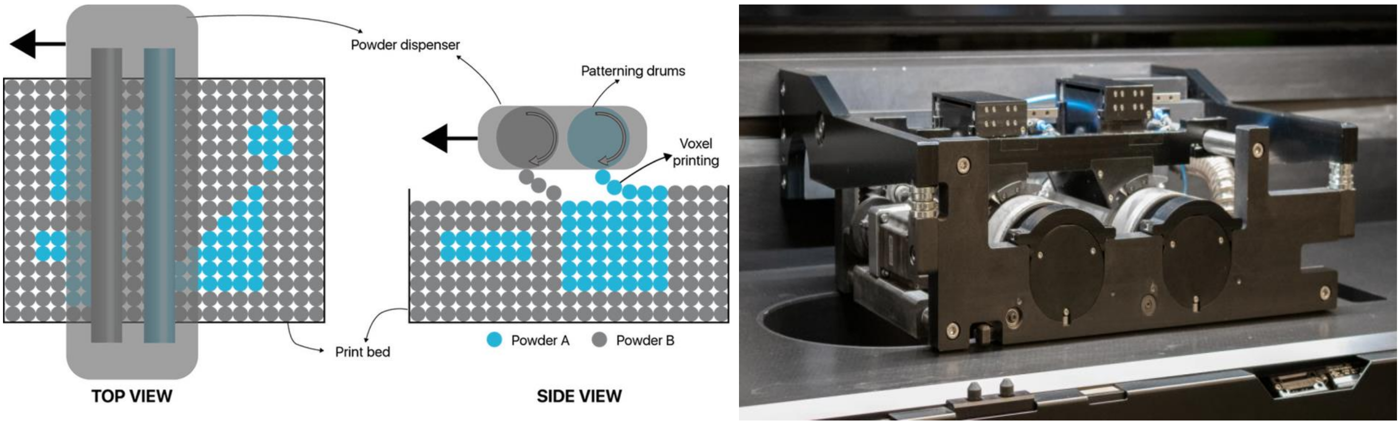


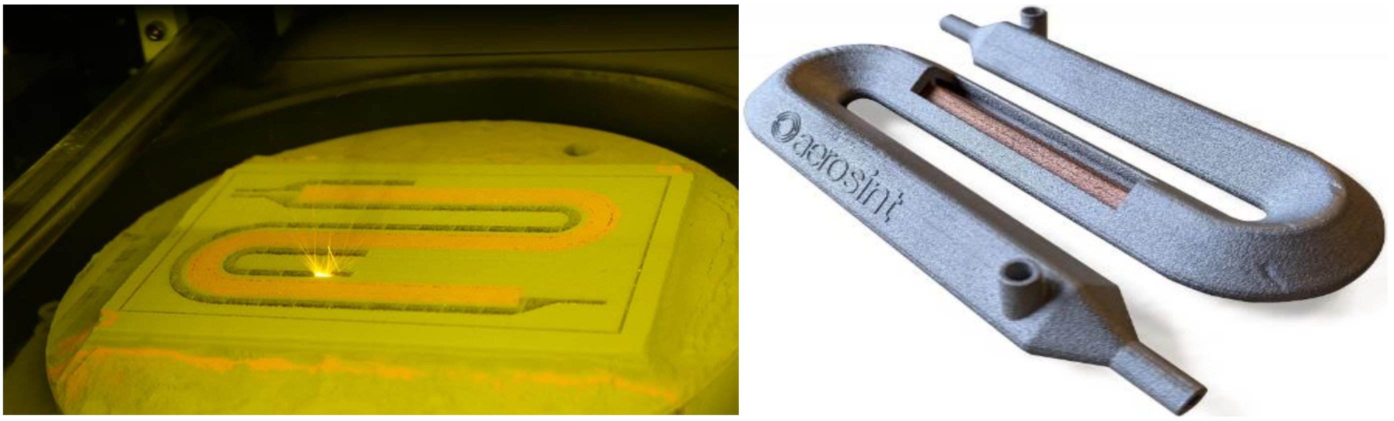

**Figure 1** Multi-material components printed using conventional laser-powder bed fusion systems. (a) 316L stainless steel to C52400 copper [17]. Reproduced with permission, copyright 2020 Elsevier. (b) NiTi to Ti6Al4V [18]. Reproduced with permission, copyright 2020 Elsevier. (c) A1.2367 tool steel to $ZrO_2$-$Al_2O_3$ blend [16]. Reproduced with permission, copyright 2022 Springer Nature.

## 2.2 Patterning Drums

In 2019, Aerosint introduced to the market a low-waste multi-material selective powder deposition technology [19]. It was designed to deposit dry powder particles (of polymer, metal or ceramic) to form a single layer containing at least two materials. This is achieved through rotating patterning drums, where one drum deposits one material, hence at least two drums are required for multi-material deposition. The process is based on the selective deposition voxel of powder in a layer-by-layer fashion [10]. The technology is capable of forming powder beds at 200 mm/s and is designed to be less sensitive to powder characteristics than conventional spreading systems [20]. Figure 2 shows the Aerosint patterning drums and a stainless steel-copper heat exchanger printed with this technology.




(a) (b)




(c) (d)

**Figure 2** Aerosint's commercial selective powder deposition technology for multi-material laser-powder bed fusion. (a-b) Dual powder recoater [21,22], (c) CuCrZr-316L powder bed [21] and (d) the resulting printed heat exchanger component [23]. Reproduced with permission, copyright Aerosint SA.

## 2.3 Powder Spreading with Removal by Suction

Another approach for applying powders in a multi-material process combines a full-surface powder deposition with powder removal by suction [24]. An illustration of this approach is shown in Figure 3 where an AconityONE printer was upgraded with a multi-material mobile module that can be installed and removed. In this configuration, tool steel 1.2709 (powder A) and copper alloy 2.129 (powder B) powders were applied by pairing the conventional powder supplier with a second powder conveying system. At first, powder A was spread and selectively melted. Then, the suction unit removed the unsolidified powder A. After that, powder B was delivered and selectively melted. This cycle was repeated for consecutive powder layers [25,26].

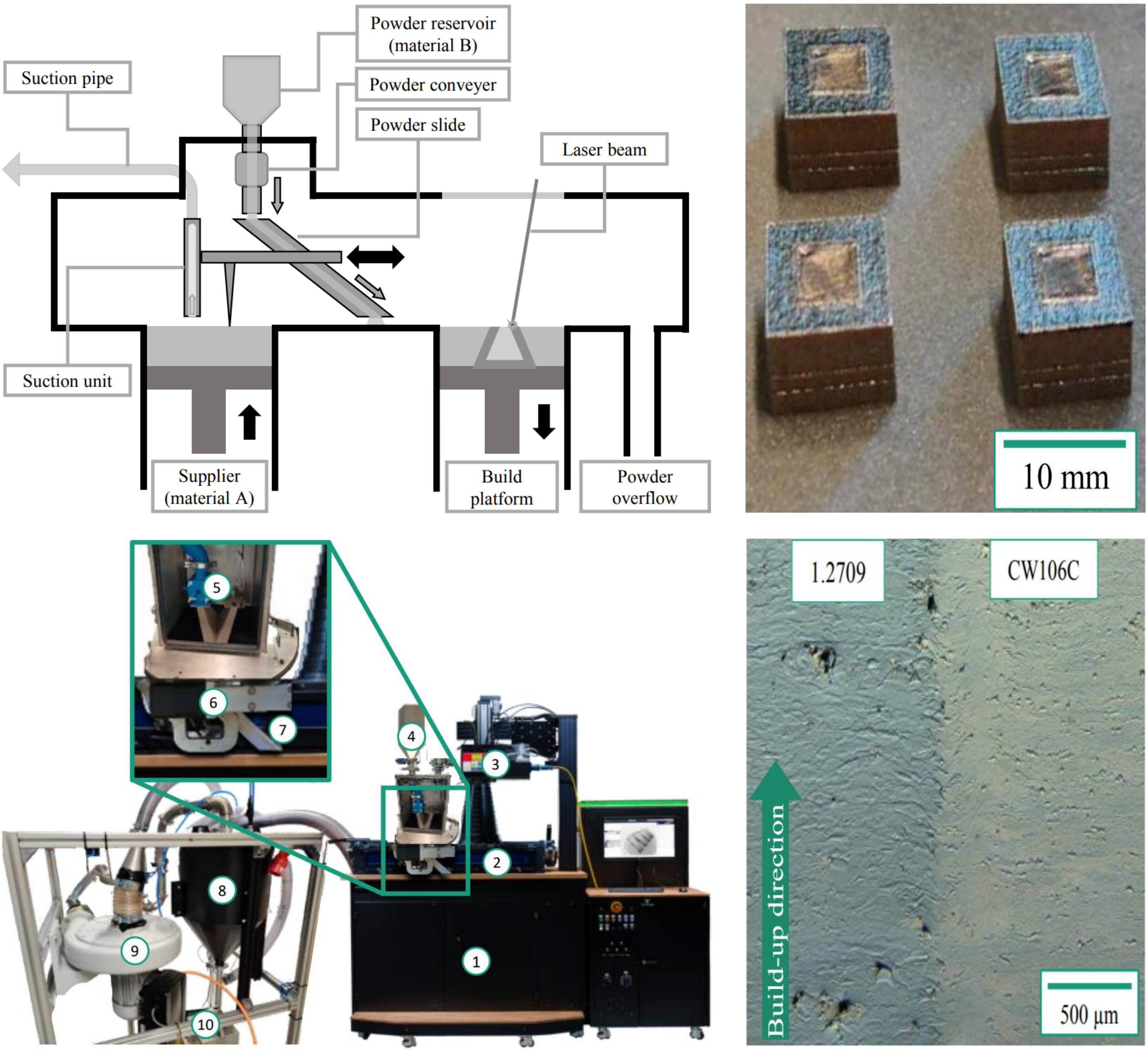



**Figure 3** A conventional single-material laser-powder bed fusion printer implemented with a multi-material mechanism. 1: AconityONE; 2: process chamber; 3: scan head; 4: powder reservoir (material B); 5: powder conveyor; 6: recoater and suction unit; 7: powder slide; 8: cyclone separator; 9: vacuum pump; 10: electronic control unit [26]. Reproduced with permission, copyright 2022 Elsevier.

## 2.4 Vibrating Nozzle

The ultrasonic vibration-assisted powder delivery system with a vortex suction nozzle is currently the most researched approach for multiple powder delivery. As it is illustrated in Figure 4, it is possible to deposit up to six discrete powder materials within one layer. Here, powders are locally deposited by means of nozzles with small orifice diameters [27]. When the valve of the powder column is opened, the gravity flow condition is achieved. However, several factors affect the potential and kinetic energy of the powder [28]. Therefore, to allow for a controlled fluidisation of the powder, gas pressure assistance can be used [29]. Nevertheless, ultrasonic vibration-assisted powder dispensing is commonly employed as powder flow rates can be more effectively and accurately regulated by controlling the electrical pulses to the piezoelectric transducer [30–32].

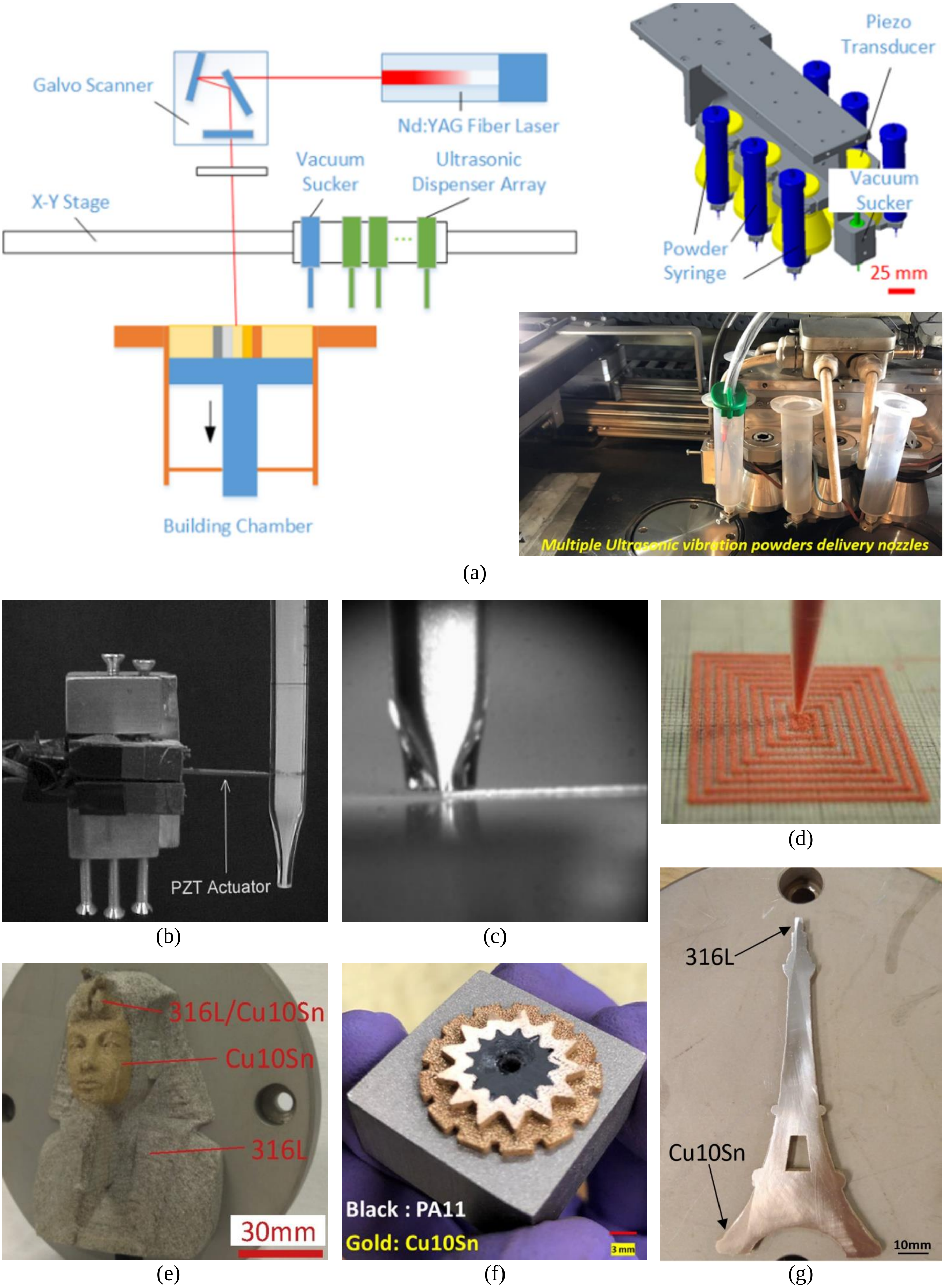
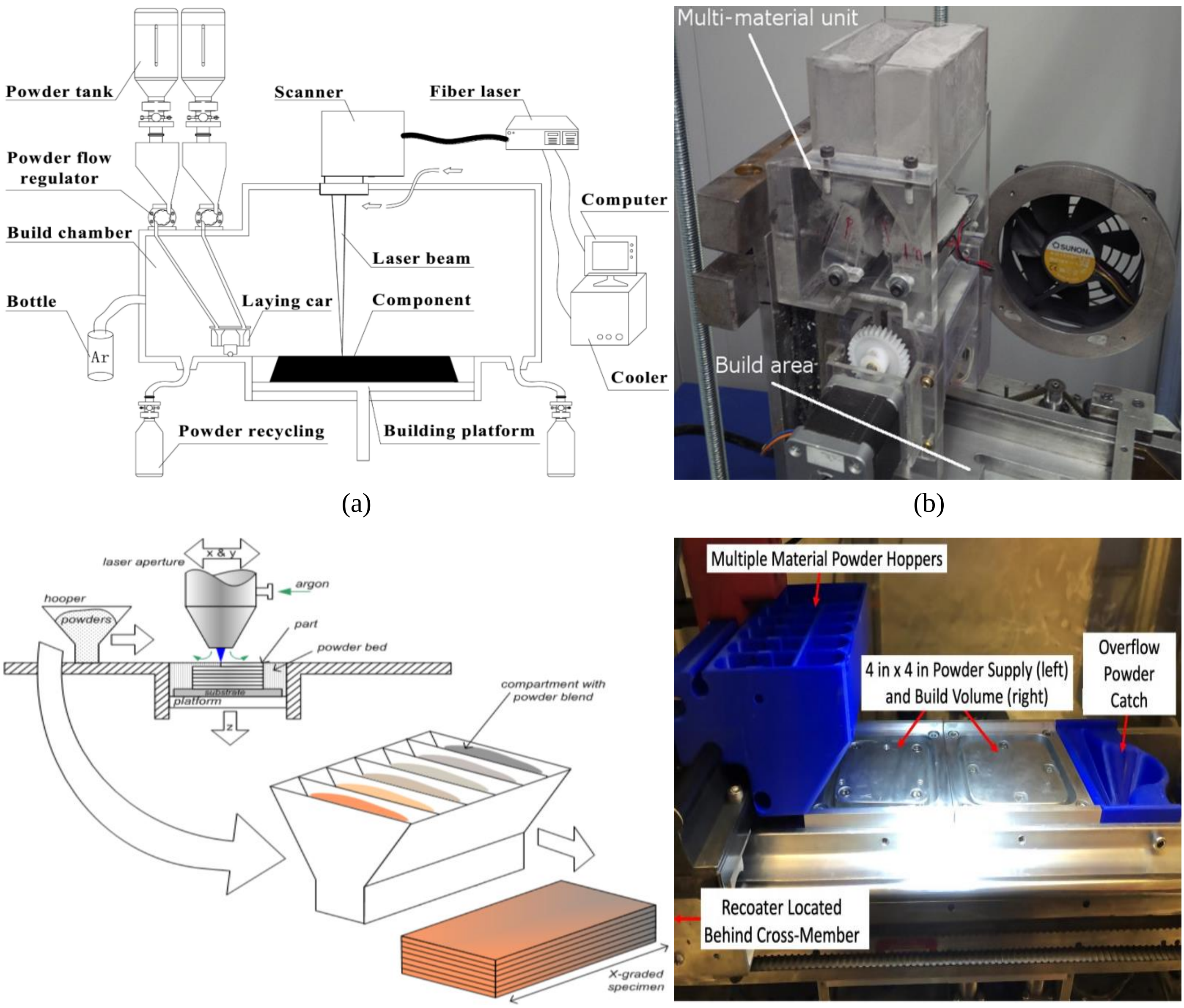

Galvo Scanner
Nd:YAG Fiber Laser
Vacuum Sucker
Ultrasonic Dispenser Array
X-Y Stage
Building Chamber
Piezo Transducer
Vacuum Sucker
Powder Syringe
25 mm
Multiple Ultrasonic vibration powders delivery nozzles
(a)
PZT Actuator
(b)
(c)
(d)
316L
Cu10Sn
10mm
(g)
316L/Cu10Sn
Cu10Sn
316L
30mm
(e)
Black : PA11
Gold: Cu10Sn
3 mm
(f)

**Figure 4** (a) Illustration of the ultrasonic vibration-assisted powder delivery system with a vortex suction nozzle [32,33]. Reproduced with permission, copyright 2019 and 2020 ASME. (b-c) Powder deposition nozzle [28,34]. Reproduced with permission, copyright Laboratory for Freeform Fabrication and University of Texas at Austin. (d) 0.8 mm in linewidth deposited soda-lime powder [28]. Reproduced with permission, copyright Laboratory for Freeform Fabrication and University of Texas at Austin. (e-g) Printed multi-material components [35–37]. Reproduced with permission, copyright 2018 and 2020 Elsevier and University of Manchester Innovation Factory.

### 2.5 Hopper Powder Feeding

Powder hoppers housing separated powders can be operated singularly for single-powder processing or can be used simultaneously for blending multiple powders at a desired composition. Typically placed externally and above the processing chamber, powder hoppers are operated with piezoelectric transducers and solenoid valves to control the unloading of powder [38,39], see Figure 5(a-b). The material discharged is then spread onto the powder bed using a coating blade system [40]. This mechanism allows for discrete and gradient material transitions along the build direction [41]. Alternatively, the mechanism shown in Figure 5(c) is capable of depositing six different powders in the same layer. Here, aligned and close-packed hoppers slide over the build platform spreading the powders in trails forming a rainbow-like powder bed of multi-material [42]. The mechanism shown in Figure 5(d) also combines a conventional powder spreading recoater with a hopper module, but it is equipped with a vacuum nozzle for powder suction [43,44]. Therefore, it is possible to deposit multiple different materials at specified locations, allowing for the printing of multi-material components with site-specific functionality.




(a) (b)

(c) (d)

**Figure 5** Prototypes of powder hopper mechanisms for (a-b) dual material [45,46]. Reproduced with permission, copyright 2019 Elsevier and 2020 Elsevier. (c-d) Multiple material deposition [42,43]. Reproduced with permission, copyright Laboratory for Freeform Fabrication and University of Texas at Austin and 2021 Elsevier.

The discrete and gradient material transitions observed in the laser-powder bed fused components in Figure 6 were achieved using hopper powder feeding mechanisms. Therefore, the existing hopper powder feeding mechanisms fulfill both inter- and intra-layer material variations.

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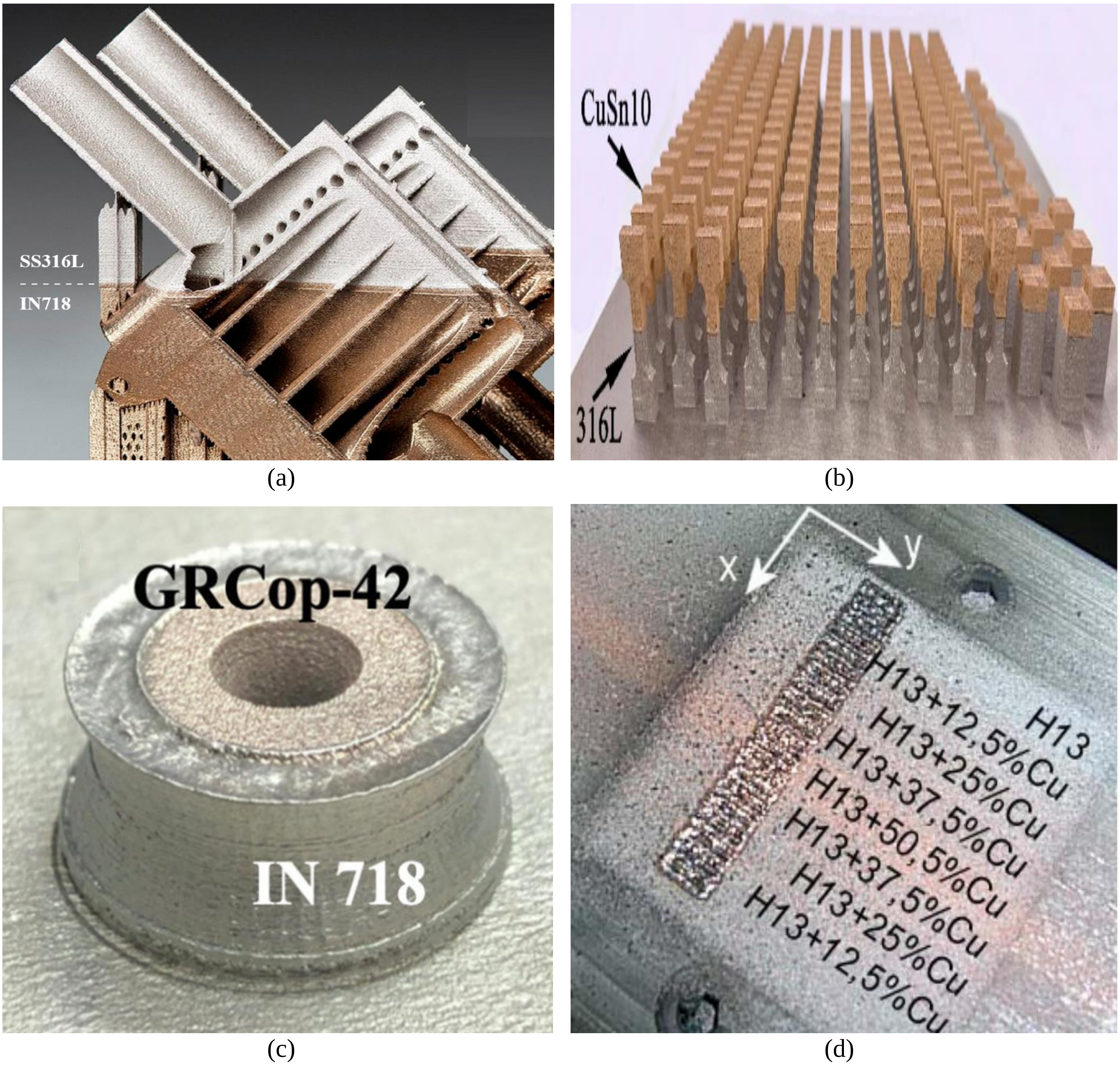


**Figure 6** Discrete and gradient material transitions in components printed from powder layers formed by powder hoppers. (a) 316L-IN718 heat exchanger [47]. Reproduced with permission, copyright 2021 Elsevier. (b) 316L-CuSn10 tensile specimens [38]. Reproduced with permission, copyright 2020 Elsevier. (c) IN718-CRCop-42 bushing [43]. Reproduced with permission, copyright 2021 Elsevier. (d) H13-Cu specimen of graded material composition [42]. Reproduced with permission, copyright Laboratory for Freeform Fabrication and University of Texas at Austin.

### 2.6 Alternating Powder Deposition

New powder deposition mechanisms for laser-powder bed fusion are needed to achieve economic, efficient and simple multi-material processing. For example, the alternating powder deposition mechanism uses the powder recoating approach to spread one or more powders at any build layer to laser-powder bed fuse sandwich-structures also known as 2D hybrid components [48]. The powder deposition system of Figure 7(a) is based on two aligned opposing recoaters [49], whereas in the system illustrated in Figure 7(b) multi-materials spreading is achieved by recoaters arranged perpendicular to each other [50]. The dual powder carrier alternating recoater shown in Figure 7(c) is designed with a centre separator which separates the front shaft from the back shaft. This system is configured to deposit one powder in each recoating direction [51]. The ringblades powder deposition system illustrated in Figure 7(d-e) can be easily operated with up to four different powders [52,53]. It can deposit a new powder layer in approximately 5 s and the powder reservoirs can be refilled or replaced within 3 min [53]. This is a small-scale alternating powder deposition system hence is best suitable for micro laser-powder bed fusion processing [54].

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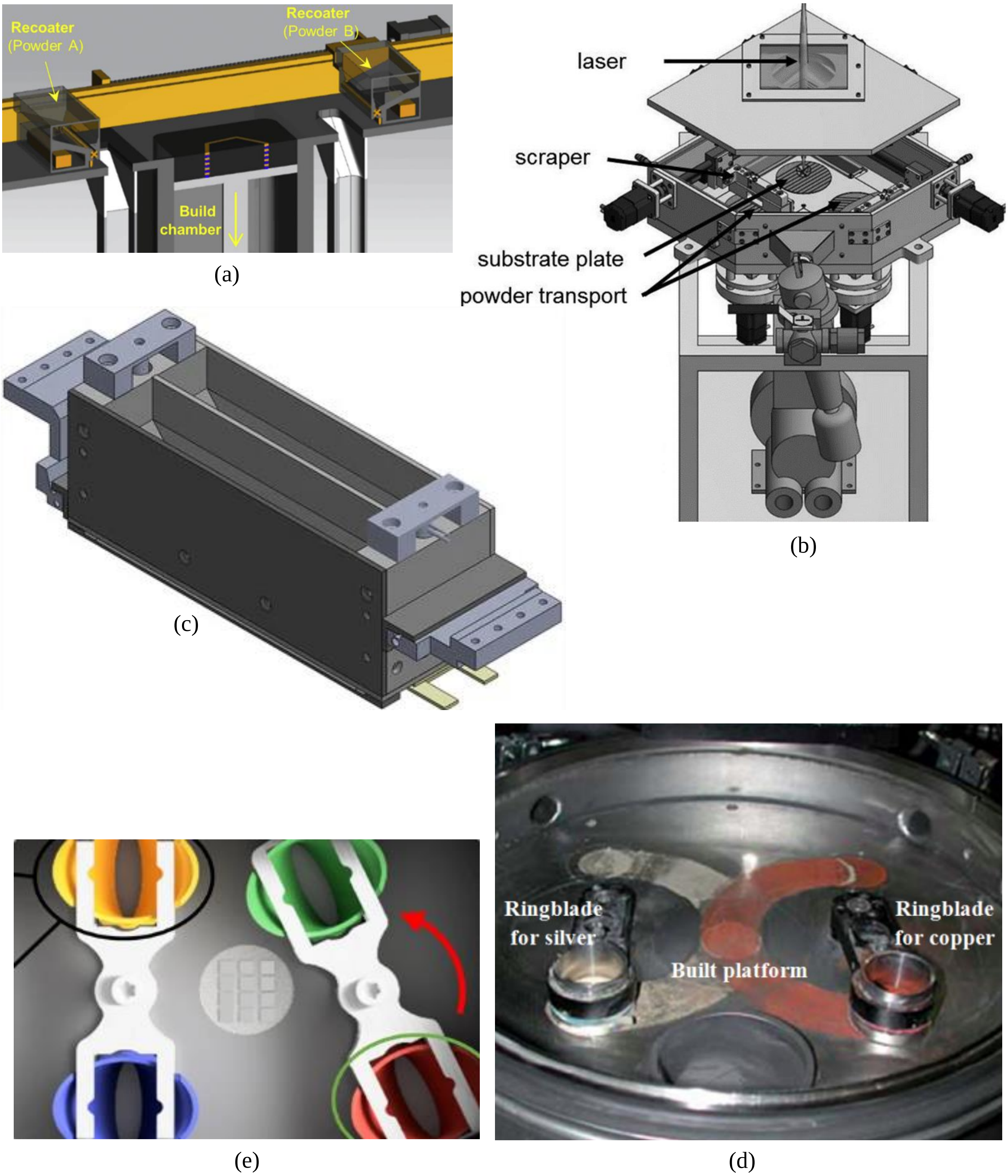


**Figure 7** Alternating powder deposition systems for laser-powder bed fusion of multi-material components. (a) Two opposing recoaters [49]. Reproduced with permission, copyright 2020 Elsevier. (b) Two perpendicular recoaters [50]. Reproduced with permission, copyright 2019 Elsevier. (c) Dual powder carrier alternating recoater [51]. Reproduced with permission, copyright 2022 Springer Nature. (d) Two ringblades powder spreaders [54]. Reproduced with permission, copyright 2007 WILEY-VCH. (e) Four ringblades powder spreaders [53]. Reproduced with permission, copyright 2022 Springer Nature.

### 2.7 Electrophotographic Powder Deposition

Electrophotographic metal powder transfer for laying patterned layers composed of multiple powders is a very promising approach. However, fundamental research is required to understand the different effects existing in this process. Figure 8(a-b) show two experimental setups which are based on this technology [55,56]. The working principle of electrophotographic powder deposition is summarised below. A photoreceptor is uniformly charged to a specified charge density using an electrical corona [57]. After that, the photoreceptor is selectively discharged by laser exposure as per layer data [58,59]. Thus, an electrostatic image containing powder data of the component for a specified layer is created [60,61]. Next, the photoreceptor is brought close to the powder supplier causing powder particles to attach to the appropriated charged areas of the photoreceptor [62]. Then, the developed powder image is transferred onto the charged build substrate by electrostatic attraction force [63]. In the final step, the photoreceptor is cleaned off with a blade to remove residual particles and also discharged with a second laser exposure before the start of the next powder deposition cycle [64,65]. Figure 8(c) illustrates a copper-iron composed powder layer deposited via this electrophotographic approach.

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(a)
(b)
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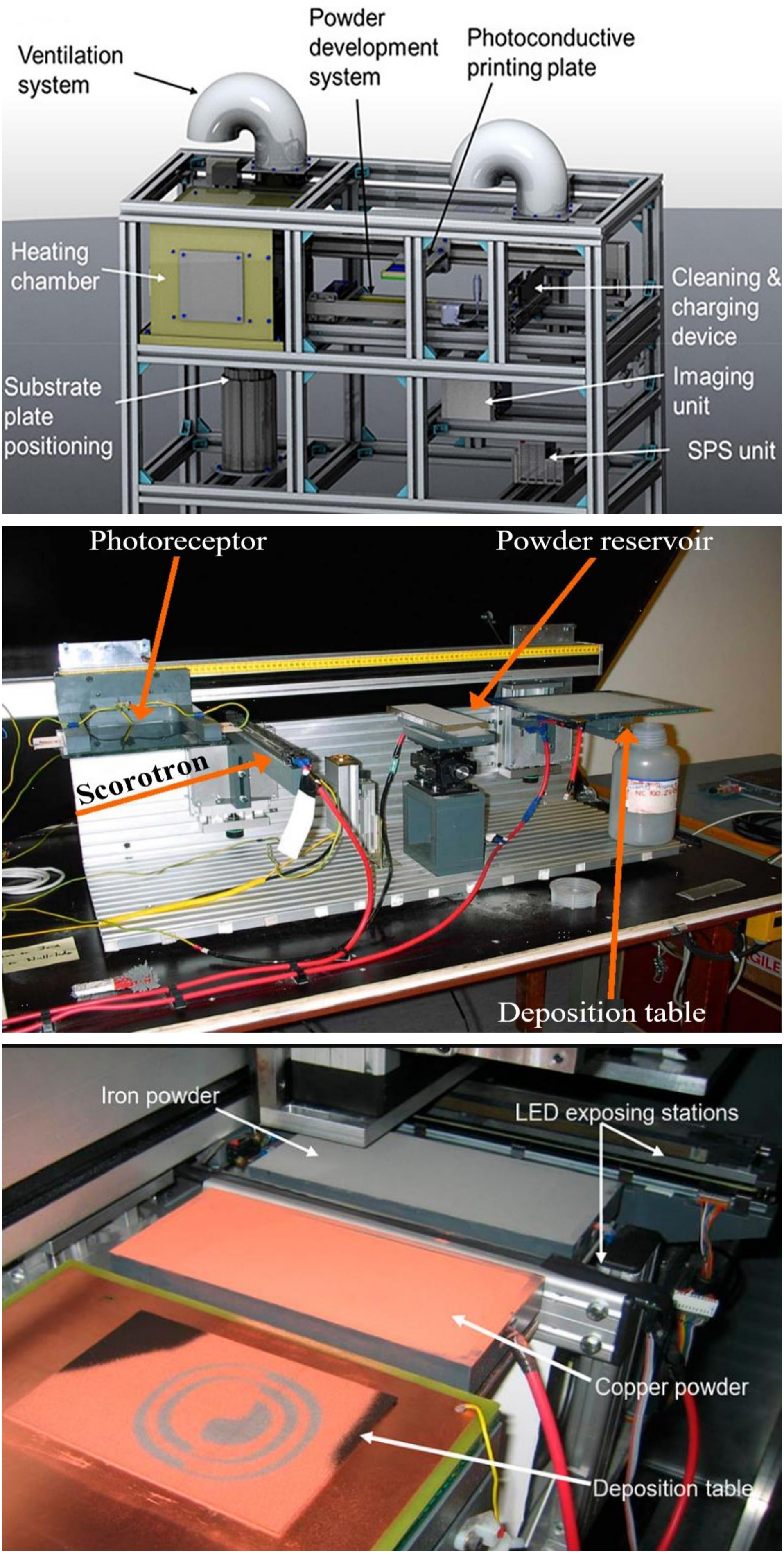

**Figure 8** Electrophotographic powder transfer system for depositing multiple powders in the same layer. (a) A electrophotographic machine design [66]. Reproduced with permission, copyright 2018 Elsevier. (b) Light-emitting diode exposing station [67]. Reproduced with permission, copyright SINTEF Norway. (c) Single layer copper and iron powder deposition [67]. Reproduced with permission, copyright SINTEF Norway.

## 3. Challenges

### 3.1 Multi-Powder Deposition

Although considerable progress has been achieved in multiple material deposition, substantial research is still required. Also, there is a lack of guidelines in terms of capabilities and applications for the existing multi-material deposition approaches. Furthermore, it is challenging to integrate multi-material deposition systems into the existing conventional laser-powder bed fusion printers [26]. This is primarily due to the complex architecture, size and functional requirements of multi-material deposition systems, and also because most of the commercial printers are closed-source systems. It is worth pointing out that current efforts in multi-material processing concentrated on the development of material deposition systems. However, attention is also required to the process development point of view.

### 3.2 Multi-material Processing

The current efficiency and precision in depositing gradient and patterned multiple powders need to be improved to comply with basic application requirements that enable printing useful multi-material components [36]. In the future, several unique proprietary powder deposition systems for the laser-powder bed fusion of multi-material components should be established.

Due to the different chemical, physical, optical and thermal properties of materials, input parameters for processing layers with multiple powders demand for careful consideration and comprehensive optimisation studies. In comparison to single-material, multi-material processing is considerably more challenging and the adoption of unsuitable input parameters can lead to the printing of components with undesirable properties, including many metallurgical defects such as porosity, balling, cracking and delaminations [68].

In multi-material printing cross-contamination between materials is an important issue to be addressed. Powder deposition systems equipped with vacuum pump provides the best option to reduce contamination [43]. Recycling of powders from multi-material processing is challenging as the powders cannot be easily separated from each other. The use of powders of different particle size distributions, which can be sorted and recycled by sieving, is not always a viable solution [69]. Powder separation based on the ferromagnetic properties of one powder and the powder sedimentation process can be used for powder separation where applicable [70]. However, optimum solutions are to minimise and prevent powder contaminations as powder recycling approaches can alter the powder properties and cause moisture and oxygen pick up [71–74]. Table 1 contrasts the multi-powder deposition systems for L-PBF. It reveals that each of them has its own advantages and disadvantages. Therefore, the selection of one multi-powder deposition system over another may be determined by the printing orientation and multi-material design of the component to be printed.

**Table 1** Overview of the advantages and disadvantages of the various multi-powder deposition systems for L-PBF.

| System | Single powder | Powder blends | Multi powder | Polymeric powders | Metallic powders | Ceramic powders | PPPCCL | OPPLLT | GPDWOL | DPDWOL | LPTFPB |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Conventional spreading | ✓ | ✓ | | ✓ | ✓ | ✓ | L | ✓ | | | T |
| Patterning Drums | ✓ | | ✓ | | ✓ | ✓ | H | ✓ | | ✓ | S |
| Spreading plus suction | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | L | ✓ | | ✓ | VS |
| Vibrating Nozzle | ✓ | ✓ | ✓ | | ✓ | ✓ | M | ✓ | ✓ | ✓ | VS |
| Hopper feeding | ✓ | ✓ | ✓ | | ✓ | ✓ | H | ✓ | ✓ | ✓ | S |
| Alternating | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | M | ✓ | | | T |
| Electrophotographic | ✓ | | ✓ | | ✓ | ✓ | H | ✓ | | ✓ | VS |

PPPCCL = Post Printing Powder Cross Contamination Level; L = Low; M = Medium; H = High; OPPLLT = One Powder Per Layer (Material Transition Between Layers); GPDWOL = Gradient Powder Deposition Within One Layer; DPDWOL = Discrete Powder Deposition Within One Layer; LPTFPB = Level of Productivity (Time to Form a Powder Bed), T = Tolerable; S = Slow; VS = Very Slow

### 3.3 Market for Multi-Material Printers

Multi-material laser-powder bed fusion is a disruptive technological innovation to its parent single-material processing. Besides processing single-material components, multi-material printers also process 2D hybrid, functionally graded and 3D multi-material components. As per the reviewed literature, many remarkable results have been reported over the last couple of years, offering significant potential to revolutionise the next generation of functional components. In fact, commercial multi-material laser-powder bed fusion printers have been gaining market ground, and a great market potential can hence be expected for multi-material components.

## 4. Future Perspectives

Research in the field of multi-material laser-powder bed fusion is relatively new and in the infancy stage. Therefore, there is a need for accelerated trials and investigations for actual applications of multi-material components to come to fruition. On this basis, the perspectives on research opportunities, material developments and research and development approaches for multi-material laser-powder bed fusion are process optimization, process monitoring, closed-loop control, system improvement, process simulation and functionality and performance enhancements.

It is envisaged that it will be possible to arbitrarily deposit colloids onto powder beds to improve material processability and to further functionalise material composition [5]. Currently, the lack in flow properties of pure and dried nano-sized powders prevent them from being deposited with conventional powder deposition systems. Via the electrophotographic metal powder transfer approach, pure nano-sized multi-powder laser-powder bed fusion will be possible. This means the deposition of nano-thick layers, which opens up a spectrum of possibilities for complexity and functionality, but at this time at the nano-scale.

## 5. Concluding Remarks

An analysis of the available literature on multi-material processing by laser-powder bed fusion has revealed its importance and explored the possibilities it offers in expanding laser-powder bed fusion applications. Multi-material laser-powder bed fusion will be increasingly employed for manufacturing 2D hybrid, functionally graded and 3D multi-material components. The most significant achievements in multi-material deposition were revealed with the patterning drums, electrophotographic powder transfer and vibrating nozzle systems. This was due to their capability of depositing discrete powder materials within one layer with reasonable accuracy. However, despite significant advances in multi-material processing over the last few years, there exist many outstanding problems, such as the serious issue of powder cross-contamination. Therefore, contamination management between material systems is a challenge to be faced. There is also an urgent need for an in-depth analysis of the multi-material laser-powder bed fusion process, so that the knowledge generated can be used in optimising and improving the process to the specific needs. The most predictable potential of multi-material will be a revolutionary movement in laser-powder bed fusion forcing the modernisation and growth of the additive manufacturing industry while offering an opportunity for the manufacturing of functional components not possible of manufacturing to date.

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