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CRITICAL REVIEW

Powder-based laser hybrid additive manufacturing of metals: a review

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Abstract
Recent advances in additive manufacturing (AM) have attracted significant industrial interest. Initially, AM was mainly associated with the fabrication of prototypes, but the AM advances together with the broadening range of available materials, especially for producing metallic parts, have broaden the application areas and now the technology can be used for manufacturing functional parts, too. Especially, the AM technologies enable the creation of complex and topologically optimised geometries with internal cavities that were impossible to produce with traditional manufacturing processes. However, the tight geometrical tolerances along with the strict surface integrity requirements in aerospace, biomedical and automotive industries are not achievable in most cases with standalone AM technologies. Therefore, AM parts need extensive post-processing to ensure that their surface and dimensional requirements together with their respective mechanical properties are met. In this context, it is not surprising that the integration of AM with post-processing technologies into single and multi set-up processing solutions, commonly referred to as hybrid AM, has emerged as a very attractive proposition for industry while attracting a significant R&D interest. This paper reviews the current research and technology advances associated with the hybrid AM solutions. The special focus is on hybrid AM solutions that combine the capabilities of laser-based AM for processing powders with the necessary post-process technologies for producing metal parts with required accuracy, surface integrity and material properties. Commercially available hybrid AM systems that integrate laser-based AM with post-processing technologies are also reviewed together with their key application areas. Finally, the main challenges and open issues in broadening the industrial use of hybrid AM solutions are discussed.

1 Introduction

The advances of additive manufacturing (AM) technology have broaden its application areas and AM is becoming a viable option for producing completely functional metal parts. In fact,

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metal AM is currently applied in the most demanding industrial sectors, i.e. aerospace [1], energy [2], defence [3], and biomedical [4, 5]. The technology allows the generation of parts with a complex topologically optimised geometry with internal cavities that were impossible to create with traditional manufacturing processes. However, tight tolerances and strict surface integrity requirements cannot be achieved by employing standalone AM technologies in most cases. Therefore, AM parts commonly require some post-processing to meet requirements associated with surface finish, dimensional tolerances and mechanical properties. So, it is not surprising that the integration of AM with post-processing technologies into single and multi set-up processing solutions, commonly referred to as hybrid AM, has emerged as a very attractive proposition for industry while attracting a significant R&D interest.

In this context, the paper is focused on hybrid manufacturing solutions that combine the capabilities of laser-based AM technologies for consolidating metal powders with post-processing ones, e.g. machining, heat treatments and surface finishing, to produce parts with required accuracy, surface

integrity and material properties. This includes both the integration of post-processing technologies in the same set-up with the laser-based AM processes but also sequentially in multi set-up hybrid solutions. In order to consider multi set-up solutions as hybrid, special fixtures or geometrical references should be employed to minimise part-positioning errors. Such single and multi set-up hybrid AM solutions offer capabilities for producing metal parts with higher complexity without compromising their accuracy, surface integrity and material properties. The potential of such hybrid AM manufacturing routes has attracted a significant industrial and research interest. The R&D efforts were focused both on broadening their application areas and on investigation and further development of their capabilities. This is evident from the constantly growing number of the published papers in this field over the past 10 years as shown in Fig. 1.

Additionally, in Fig. 2, it is shown that among the different heat sources employed in additive manufacturing processes, laser power has gained the highest interest from the research community (31% of published research works are focused on laser-based additive manufacturing processes). Considering the growing importance of laser-based additive manufacturing technologies, as mentioned above, the present work will summarise relevant research works regarding the hybrid additive manufacturing that combines laser additive manufacturing and post-processing techniques.

The structure of this review paper is as follows. The next section provides an overview of available AM technologies for producing metal parts, and then the most common laser-based AM processes for consolidating metal powders are reviewed. In particular, investigations on their limitations and respective post-processing requirements for producing metal parts are reported. Then, the research on post-processing technologies that are usually integrated with laser-based AM processes into single and multi-setup AM solutions is reviewed. Next, the benefits offered by different post-processing technologies in addressing the shortcomings of metal AM parts are discussed based on the reported
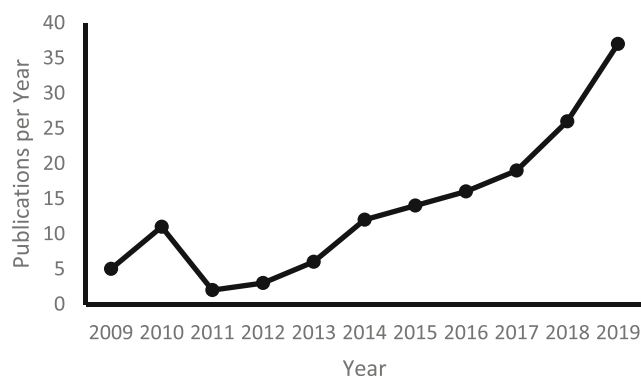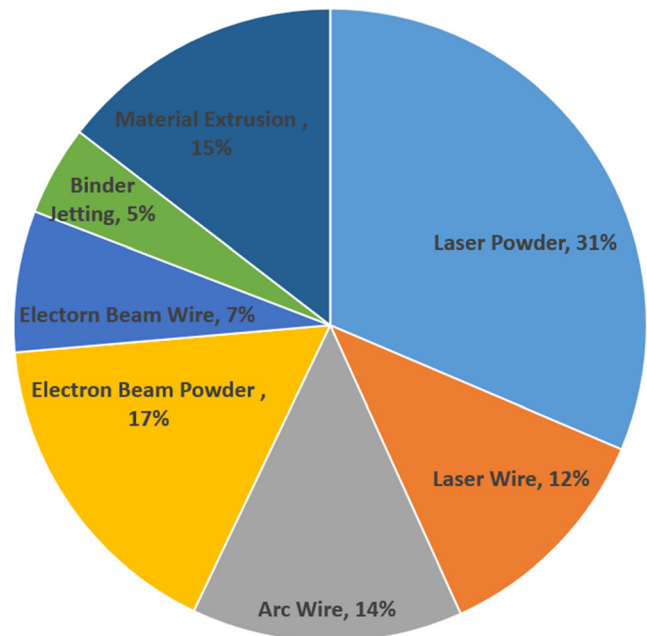
Fig. 2 Additive manufacturing articles published in 2019, [6]

research. Section 5 reviews the commercially available hybrid AM technologies, with specific focus on their advantages and limitation. Section 6 provides an overview of relevant research on main application areas for the hybrid AM manufacturing solutions. Next, Section 7 discusses the main challenges in broadening the use of hybrid AM routes for producing metal parts with required complexity and quality. Finally, conclusions are made about the reviewed hybrid AM routes.

1.1 Metal additive manufacturing processes

AM encompasses all technologies for producing parts in layer-by-layer fashion directly from CAD models. Initially, AM technologies were mostly applied for fabricating prototypes quickly that can be used for design verification and marketing purposes. They became quickly indispensable in many application areas. However, they were still just physical models that were not supposed to fulfil any functional requirements and therefore were commonly made from non-metallic materials, such as thermoplastics, resins and ceramic powders [7]. Meanwhile, the advances of AM technologies in the last two decades, especially for building metallic parts, made possible the manufacture of functional components and thus enabling the so-called direct digital manufacturing [8].

Metallic parts can be produced by employing mainly five different categories of AM technologies, known as material extrusion, powder bed fusion, direct energy deposition, binder jetting and laminated object manufacturing (LOM) [9, 10]. Each category includes metal AM technologies that employ different methods for producing physical models, in particular:

Fig. 1 The number of published papers on hybrid additive manufacturing over the last 10 years, [6]

- Material extrusion. Thermoplastic filaments or rods loaded with a metal powder are extruded through a heated nozzle to build metal parts layer by layer. Afterwards, the thermoplastic content in the printed green parts is removed chemically and/or thermally that is followed by a sintering process to produce metal parts [5, 11].
- Powder bed fusion (PBF). The process employs a heat source, e.g. a laser or an electron beam, to fuse or melt the powder particles layer by layer. The energy beam is applied to a small region of a powder bed that incrementally drops down upon the completion of each layer. Depending on the processing temperature, the powder consolidation is done by sintering process or melting. Direct metal laser sintering (DMLS), selective laser melting (SLM) and electron beam melting (EBM) are the most widely used technologies that fall in this AM category [5, 11].
- Direct laser deposition (DLD). The process employs focused thermal energy, e.g. a laser source or arc plasma, to fuse materials by melting. In particular, metal powder or wires are fed through a nozzle at the focal spot and deposited to a heated substrate layer by layer according to a predefined path. In this AM category, laser engineering net shaping (LENS) or direct metal deposition (DMD) technologies are noteworthy [11, 12].
- Binder jetting. A binder agent is selectively deposited onto a metal powder bed to glue particles together layer by layer. Similar to the material extrusion, the binder content in the printed part is removed chemically through a debinding step and then the part is consolidated by sintering. Parts created using this method are not fully dense, and therefore, an infiltration is required to fill the porosity with metal powder [11].
- Laminated object manufacturing (LOM). It is a technique that uses ultrasonic or laser energy source to stack previously cut metal sheets to form a three-dimensional object [13]. This technology is also referred to as sheet lamination (SL).

The schematic diagram shown in Fig. 3 presents a classification of existing AM technologies for producing metal parts. In the figure, the processes that fall within the scope of this review are highlighted. As was already mentioned, this review is focused on single and multi-setup hybrid AM routes that employ laser-based AM process to consolidate metal powders.

In addition to the four metal AM technologies discussed so far, another technology called cold spray additive manufacturing (CS or CSAM) has been attracting some research interest. CS is a material deposition process that was initially developed for coating/cladding purposes but has recently been employed as a metal AM process to build and repair components [14]. Materials are deposited by accelerating fine powder particles to a critical speed by employing a high-velocity compressed gas stream that upon the impact on the substrate, a metallurgical bond and mechanical interlocks are formed to produce parts layer by layer. Laser-assisted cold spray has also been subjected to investigation as an improved alternative to the CS process. Bray et al. [15] developed a system to deposit powder particles through CS in a substrate heated by laser diode and achieved deposits with densities higher than 99%. However, the CS process is outside the scope of this review paper and will not be analysed in the following sections.

It should be noted that among all metal AM technologies, the laser-based PBF (LPBF) process has attracted the highest industrial interest due to the relatively good accuracy and surface finish that can be achieved. However, the type of parts that can be produced with this technology is limited by the size of the powder bed. Therefore, DLD or also referred to as laser-based direct energy deposition (DED) has gain significant industrial interest, too, because of its higher build rates and bigger size of the parts that can be produced. However, such flexibility is at the expense of accuracy and surface integrity of produced parts and therefore commonly they require extensive post-processing [16]. Considering the industrial interest in the LPBF and DLD technologies [17, 18] and also their often integration in hybrid AM solutions, their fundamentals and a review of relevant research on these two technologies are presented in the next section.

1.2 Laser-based additive manufacturing processes

1.2.1 Laser-based powder bed fusion

This technology is currently being used for the manufacture of mostly high-value parts. LPBF is an AM technology that employs continuous-wave laser sources to melt and fuse particles selectively onto a powder bed and thus creating three-dimensional parts layer by layer. When the particles are melted, viscous flow due to a surface tension joins them together into a melt pool. Then, the energy in the melt pool is transferred to the surrounding powder through conduction, radiation and convection [19, 20]. After the selective consolidation of areas on each layer, the powder bed is lowered and the next layer of powder is spread and thus successive layers are processed to create fully dense 3D parts [21–23]. Figure 4 shows a schematic diagram of the LPBF process.

In LPBF, process parameters, namely scan strategy, laser spot diameter, laser power, scan speed, scan line spacing and the thickness of the powder layer, have to be optimised in order to obtain the best results in terms of porosity and mechanical properties of the consolidated powder [22, 24, 25]. Laser power is considered the most influencing parameter in regards to the density (or porosity) of the final part [26]. Also,
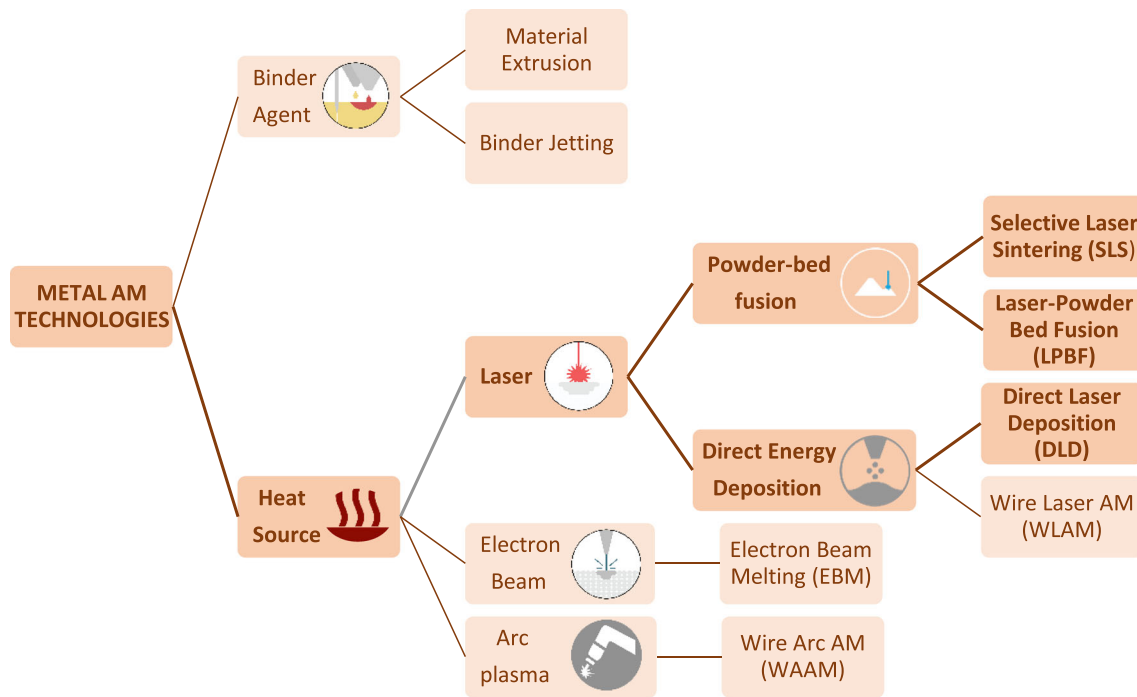
Fig. 3 Classification of metal AM technologies

powder characteristics, i.e. chemical constituents, particle shape and size and distribution, are a factor affecting the final part quality [24]. In fact, it is possible to assess the laser heat input by using the so-called "energy density function" as follows [25]:

$$\Psi = \frac{P}{\nu \cdot h \cdot t} \tag{1}$$

where P and ν are the laser power and scan speed, respectively, h is the scan spacing, and t is the layer thickness. Some studies have shown that the optimum energy density for a given material can be found and thus producing parts with as low as possible porosity. In addition to the above-mentioned process parameters, gas flow direction and flow rate in the build chamber have been identified as factors affecting the part quality [27]. Insufficient gas flow rates and

Fig. 4 Graphical explanation of the LPBF process
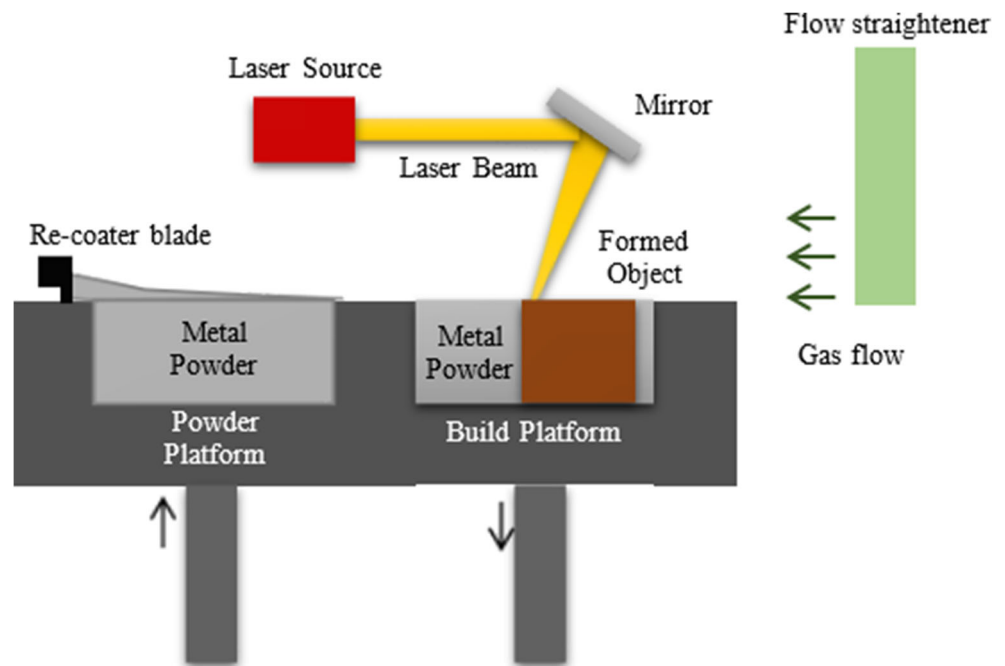
inappropriate flow directions could lead to part delamination. Furthermore, the height of the flow straightener from the powder bed and the type of the used shielding gas also affect the build quality [28].

There is a wide range of alloys available for LPBF. Among them, stainless steel (AISI 316L), aluminium, titanium and their alloys, e.g. AlSi10Mg and Ti6Al4V, and Ni-based alloys, e.g. Inconel 718, are the most widely used materials. Depending on the materials employed, different issues could arise during the LPBF process. For example, when aluminium or its alloys are used, a major issue that can affect the process is the material oxidation that could occur due to the presence of oxygen in the build chamber [29].

The available materials allow the LPBF process to be used in different industrial applications. Figure 5 shows some examples of LPBF parts produced for aerospace, i.e. a bracket and a pump, and automotive, i.e. an air duct, applications.

Recently, a number of process advances have been reported. In particular, the development of a gas atomised powder with particles that are spherical, have a higher flowability and a higher packing density can be achieved [34]. As the long build times and high part costs are some of the main issues preventing the broader use of the LPBF technology, a research to improve the process productivity and also to reduce residual stresses through the use of quad laser systems was reported [35]. In addition, LPBF systems that integrate powder handling/cleaning and part post-processing in the same build chamber have been developed and thus underpins the use of

this AM technology for series production [36]. Other process improvements include advances in gas flow systems that use sub-atmospheric pressure in the build chamber which enables better quality parts at lesser laser powers ensuring reduced overall energy consumption [37]. Also, the development of process monitoring tools has been an important R&D topic recently for researchers and manufacturing companies as a way both to understand better the underlying laser-material interactions during the process and thus improving the process control [38]. In particular, the chamber conditions, i.e. build plate temperature, ambient temperature, pressure oxygen concentration, etc., should be monitored as they have a significant effect on process behaviour and can lead to the occurrence of part defects [39]. Recently, the development of advanced monitoring systems has been reported that allow some important process parameters, such as laser power, porosity, melt-pool status, powder layer distribution on the build surface and temperature, to be controlled [40, 41].

The LPBF process offers some advantages with respect to other manufacturing processes. Especially, complex geometries can be built with this technology and parts with relatively small features and internal cavities can be created, too, with this process. It enables the manufacture of lightweight parts, i.e. topology optimised ones and parts with lattice structures, and therefore is a very attractive option for a number of applications in the aerospace industry. Additionally, the LPBF parts have high specific strength and stiffness [42, 43].

Fig. 5 Industry applications of the LPBF technology. **a** Spider bracket. **b** Manifold (photo courtesy of Renishaw) [30]. **c** A380 fuel connector [31]. **d, e** Topology optimized aerospace brackets [32, 33]
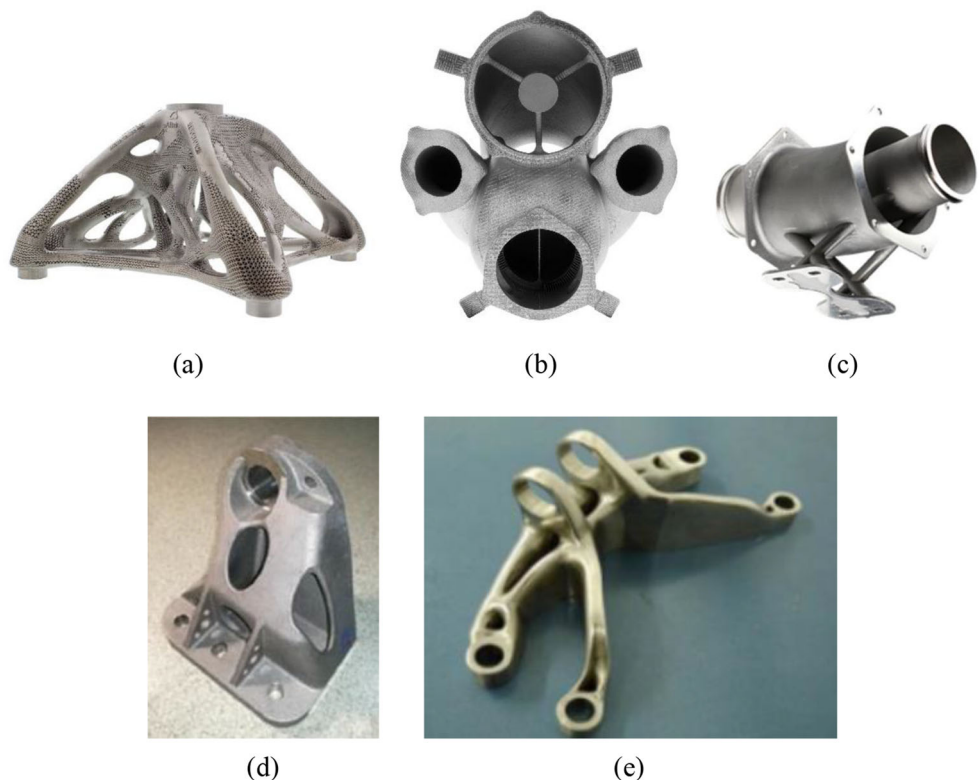
However, the LPBF technology has some limitations, too. Surface roughness of produced parts is a major issue for the broader use of this layer-by-layer process that leads to the widely known "staircase effect", particularly visible on sloping edges. Apart from process parameters, powder size is another factor that affects the resulting surface finish. When smaller particles are employed and a layer thickness is reduced, a better surface finish can be obtained. However, this is at expense of manufacturing time and cost [44]. In addition, as consequence of the high heat load during the melting process, there is a high thermal gradient in the built parts that lead to higher residual stresses and a deterioration of their fatigue behaviour [45]. LPBF has some other inherited issues that can affect the process, such as the porosity and the shrinkage of built parts. Due to liquid to solid transformations and to the inhomogeneous cooling to room temperature in the solid state, shrinkage and accumulation of residual stresses occur. Regarding porosity, instability of the melt pool [46], lack of fusion between powder particles [47] and a narrow particle size distribution can reduce the packing density [48, 49] that together with scanning strategies can promote the manufacture of low-density LPBF parts [45, 50]. Other issues include powder oxidation that could occur due to the presence of oxygen in the build chamber during the process [51]. Figure 6 depicts disconnection in LPBF parts due to residual stresses while porosity, voids and lack of fusion defects are shown in Fig. 7.

1.2.2 Direct laser deposition

The DLD technology employs a focused laser beam to fuse materials in the form of metal wires and/or powder onto a building platform and thus producing parts layer by layer [54]. As the focus of the paper is on powder-based AM processes, only the relevant research on DLD of powders is reviewed. During the DLD process, some of the laser irradiation is absorbed by the substrate on which the powder particles are delivered through a nozzle and thus a controlled melt pool is created in the laser-material interaction area [55]. Additionally, an inert gas, i.e. argon, is delivered onto the deposition area in order to minimise any metal oxidation. The process is graphically shown in Fig. 8.

The DLD system can be attached to a robot arm or integrated into a multi-axis machine so that the nozzle can follow

a specific path to generate the desired geometry layer by layer. DLD is commonly employed for applying thick coatings of workpiece and also for repairing worn or damaged parts. The latter is of growing interest in the automotive and aerospace industries due to the cost saving that the DLD process can offer.

Similar to LPBF, powder characteristics have a great impact on the quality and properties of the DLD manufactured parts. Chemical compositions of powders, particle size, distribution and morphology together with laser parameters, i.e. laser power, powder feed rate and scanning speed, have to be optimised in order to produce parts with required physical and mechanical properties [56]. Another important DLD processing parameter is the hatching or scanning strategy that defines the path of the powder deposition head. The microstructure and mechanical properties of the DLD parts can be controlled by varying the hatching strategy [57]. Additionally, the nozzle inclination angle and the set focal plane for the laser beam are important factors affecting the properties of the DLD parts [58].

The powders used for the DLD process are similar to those utilised in the LPBF process. For example, the DLD is commonly used to process the following materials: nickel-based alloys (In625, In718, In738, In713, In939, CM-247LC, Nimonic 263, Hastelloy X, Hastelloy C-276, Waspaloy, Haynes 230, MarM247), titanium alloys (Ti6Al4V, Ti-6-2-4-2, Ti-6-2-4-6, CP Ti), aluminium and its alloys (4047, 6061, 7050, 7075, AlSi7Mg, AlSi10Mg, AlSi12), iron-based alloys (17-4PH, H13, 304L, 316L, 420SS, PH 138 Mo, 155PH, AISI 4140), cobalt-based alloys (Stellite21, CM-64, Co6, CoCr) and Copper-based (Cu-Ni) and iron-nickel-chromium alloy (A286) [59]. The processing of such powders with the DLD technology is an important enabler for producing and repairing complex parts in the automotive and aerospace industries. Figure 9 shows some examples of produced and repaired parts for aerospace applications.

One important advantage of the DLD process in comparison to other AM technologies is the higher building rates that can be achieved [63]. Another important advantage of the DLD process is that the technology not only can be deployed to produce parts but also can be used to deposit materials selectively on existing parts and uneven surfaces and thus creating some complex geometries/structures or repair

Fig. 6 Some typical defects in LPBF metallic parts: disconnection from the substrate due to residual stresses in SLM manufactured parts [52]
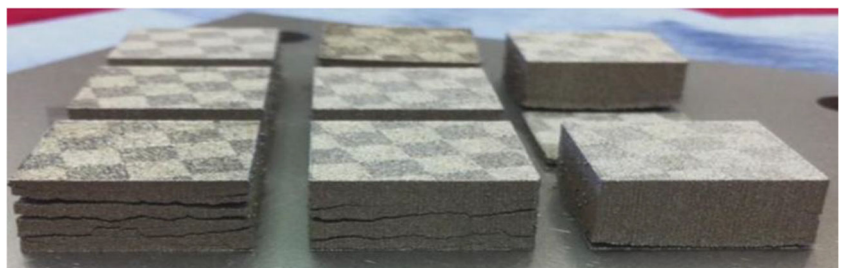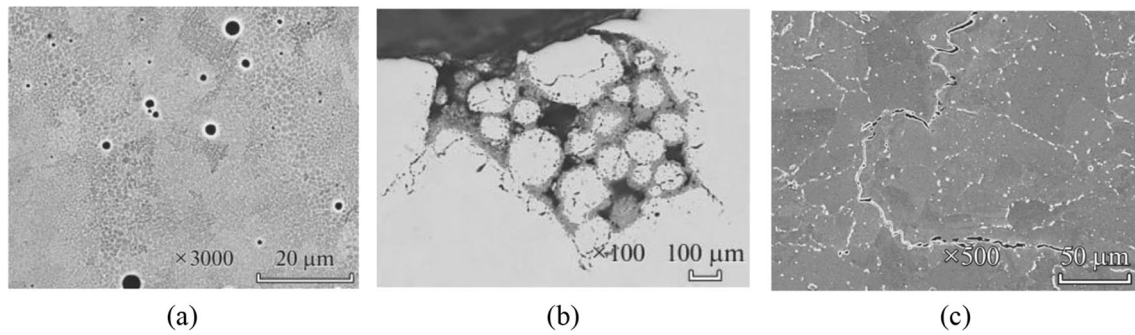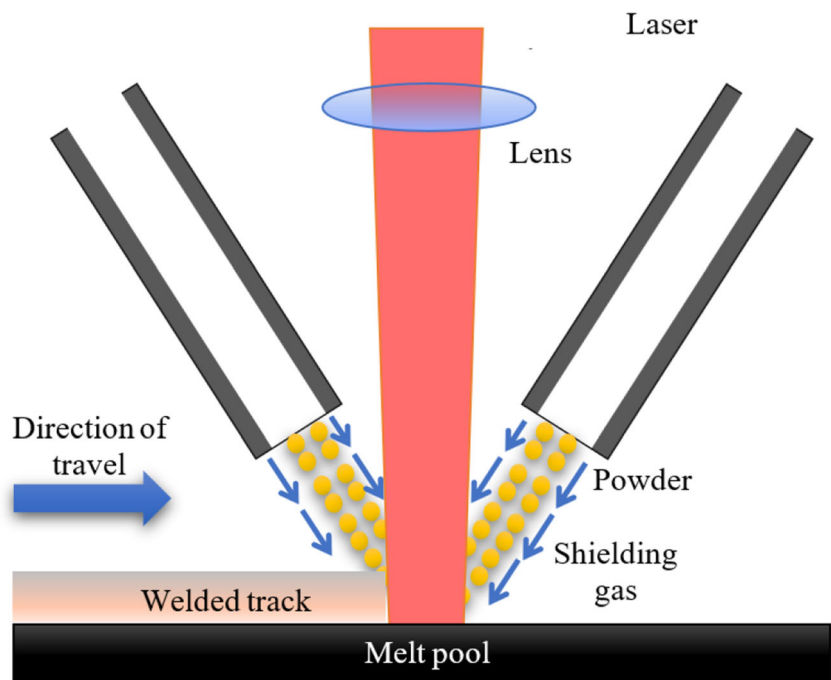
Fig. 7 More defects in metal components produced by SLM. **a** Gas pores. **b** Lack of fusion between powder granules. **c** Micro- and macrocracks [53]. The figures are reused under the Creative Commons CC-BY licence

damaged or worn out features of high-value components. Thus, the DLD technology offers significant flexibility in manufacturing and repairing metal components. Furthermore, DLD enables the use of different powder materials in the same process, sometimes even simultaneously, and thus producing parts from functionally graded materials or customised alloys [18].

However, as with the LPBF process, the DLD technology has some disadvantages and limitations, too, that have to be considered. Some of them are common across metal AM technologies and have already been mentioned in regard to the LPBF process. In particular, the achievable dimensional accuracy, surface roughness, "staircase effects", porosity and residual stresses are limitations that also apply to the DLD process. In addition, the DLD process is not usually integrated into chambers with a controlled environment; therefore, a shielding inert gas is usually used to surround the melt pool and thus minimising the powder oxidation, as shown in Fig. 8.

However, depending on the gas shielding performance of the DLD heads and the processed material, this might not be sufficient to prevent any oxidation during the deposition and thus affecting negatively the integrity of the part. Furthermore, the DLD parts show a lower hardness, higher ductility and higher toughness in comparison with the LPBF ones [64]. Figure 10 shows examples of defects that can be found in DLD parts.

1.2.3 Limitations of powder-based laser additive manufacturing for producing metal parts

Laser-based AM processes, i.e. LPBF and DLD, for producing metal parts by consolidating metallic powders are powerful methods to produce complex structures that were not achievable with conventional manufacturing technologies. Additionally, the amount of material required for their manufacture is much lower and thus a higher resource efficiency can be achieved. However, laser-based AM technologies have

Fig. 8 Schematic diagram of powder-based DLD process
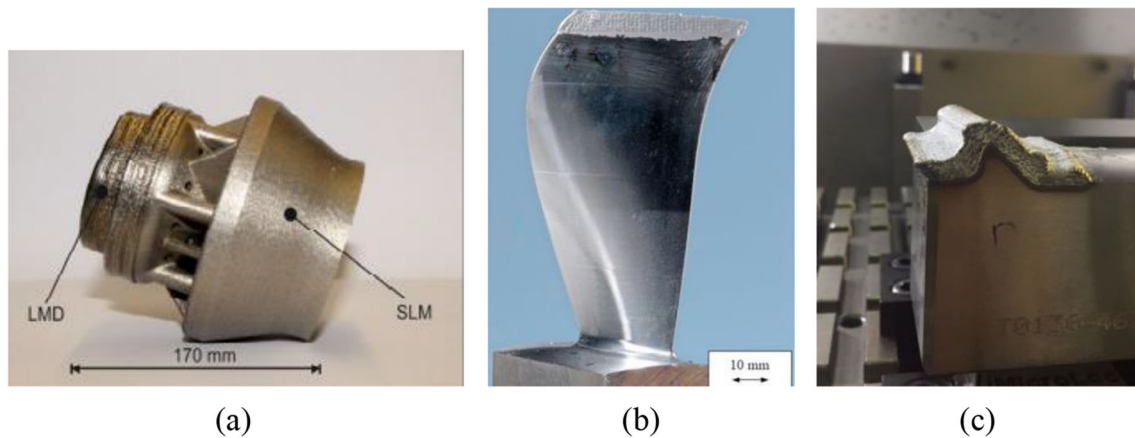
Fig. 9 Industrial applications of the DLD process. **a** Rebuilt burner [60]. **b** Blade tip repair [61]. **c** Die insert repair [62]

limitations, too, that have to be addressed in order to broaden their use by industry.

The low surface integrity and accuracy together with the porosity of the produced metal parts are some of the main limitations of these AM technologies [67, 68]. These shortcomings are even of a higher concern when manufacturing high-value and safety critical parts that have to meet stringent industrial requirements. Khorasani et al. [69] concluded that significant post-processing was required when parts with curved geometries were produced with the LPBF process in order to improve their surface roughness. It was also highlighted that some of the part surfaces could be distorted and cracks and lines could appear due to powder variations during the LPBF process. Figure 11 shows examples of issues

and defects of parts manufactured by laser-based additive manufacturing processes.

Figure 11a, b and c show examples of crack formation, unmelted and stacked powder and surface roughness in LPBF parts. Additionally, Fig. 11d shows the deformation generated by the accumulation of residual stresses. Concretely, as shown in the figure, a gap is created between two components due to the distortion. Finally, Fig. 11e shows another example of part deformation due to thermal distortion. The area highlighted in red, which was intended to be flat, presents an overhang tilt generated by this distortion.

In addition to the geometrical quality of parts, consistent mechanical properties and microstructure are also required for many applications while LPBF and DLD parts usually show a

Fig. 10 Common defects and surface quality of DLD metallic parts. **a** Crack formation during the deposition [65]. **b** Porosity [66]

(a)

(b)

(a)   (b)   (c)

(d)   (e)
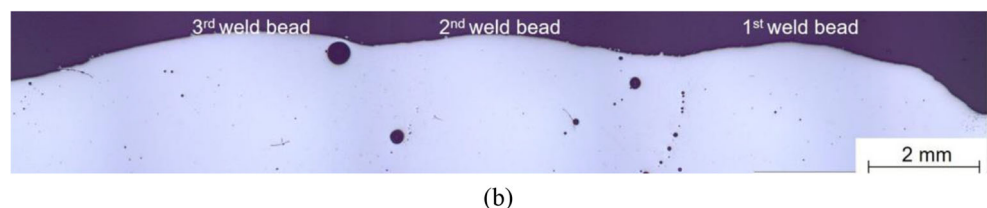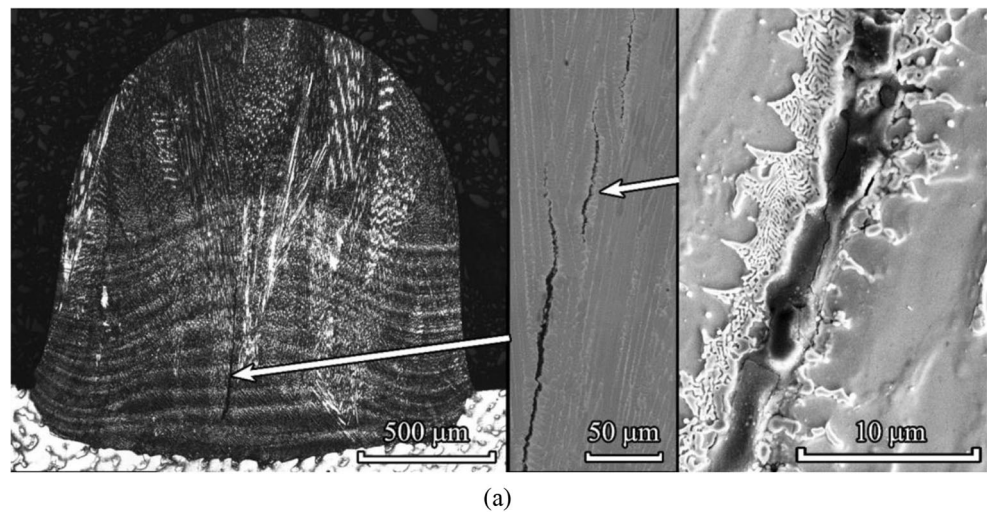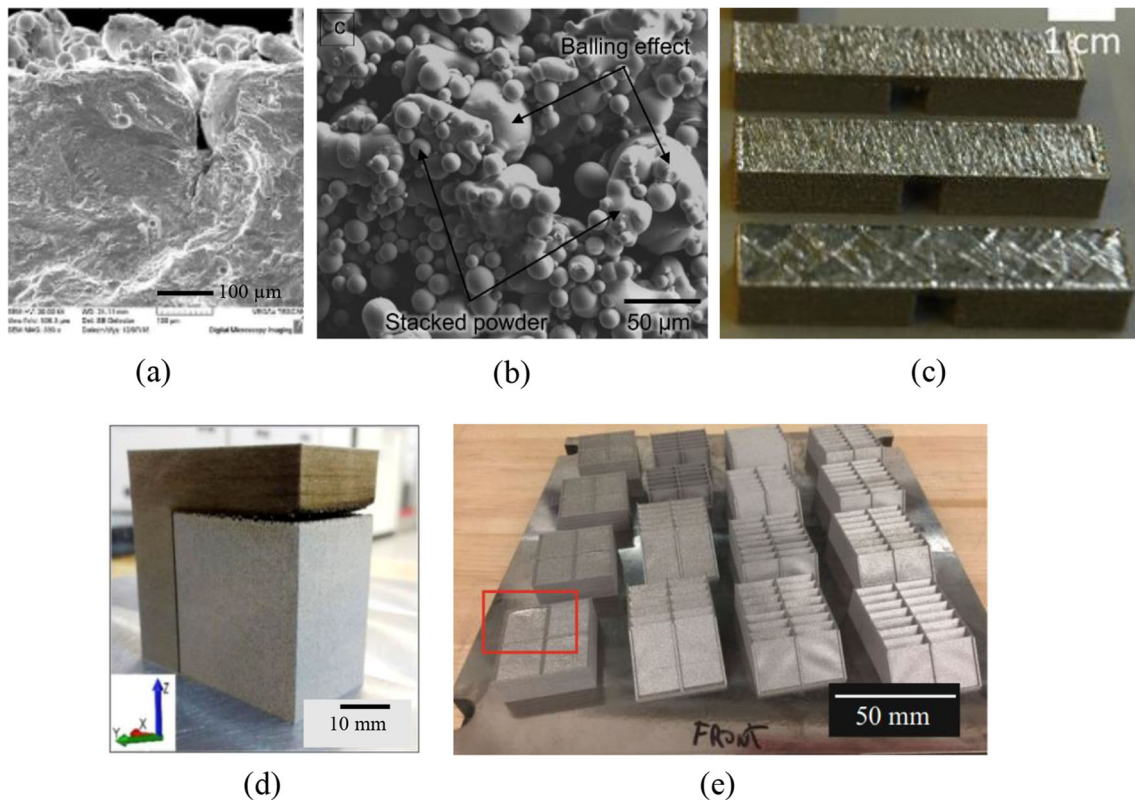
Fig. 11 Main limitations of additive manufacturing. **a** Crack formation [70]. **b** Unmelted and stacked powder [71]. **c** Surface roughness depending on the scanning strategy [72]. **d** Part deformations [73]. **e** Overhang tilt due to thermal distortion (highlighted in red) [74]

significant anisotropy [67, 75]. Another factor that has a significant impact on part properties is the residual stresses generated not only in the produced parts but also in the building substrates. As it was already discussed, residual stresses are the result of the thermal gradient that occurs during the AM process and can reduce the fatigue life of produced parts. Also, they can lead to part deformations and distortions that can cause the built structures to separate from the base or substrates and the formation of cracks and delamination between the deposited layers [45, 76].

With regard to part designs, DLD and LPBF are generally considered to provide designers with significant freedom to explore a much bigger if not unlimited design space. However, as with all manufacturing technologies, they have limitations regarding the complexity of part geometries that can be produced reliably and required repeatability. In particular, the build size in LPBF is limited by the dimensions of the building substrate and the additive system [77–79]. In 2018, Arregui et al. [80] analysed the minimum slope that can be achieved on inclined walls by DLD and concluded that for small slope angles, the laser head should be inclined so that the deposition to be carried out with a head normal to the substrate to avoid geometrical distortions. Additionally, support structures are usually necessary when DLD or LPBF is used to manufacture certain complex geometries, e.g. overhangs, undercuts and part assemblies with moving components, that are

then removed using a post-processing operation. However, the removal of such support structures by machining can become difficult and even impossible [78, 81, 82]. As a consequence, a re-design of parts can be required to eliminate or minimise the need for support structures.

The available materials for the DLD and LPBF processes are limited, and therefore, significant research efforts are focused on the development of new alloys and also on the creation of dedicated material databases and standards [68, 75, 83, 84]. Additionally, there is a significant research interest in the development of process models that can predict quality, dimensional accuracy, and mechanical properties of the produced AM parts.

Finally, when compared to conventional manufacturing methods for producing metal parts, the LPBF and DLD processes present the following shortcomings:

- High cost of the LPBF and DLD machines and the materials for them
- Relatively low production rates are important shortcomings [67, 85].
- Powder recyclability could be a solution to high material costs in PBF processes. However, the powder morphology might be affected when a recycled material is used, and this can impact the part density, hardness and mechanical properties [86]. Furthermore, the recycling process should

ensure that any partially melted or highly heated particles are separated from those that will be reused [87–89].

- Depending on the metallic powder used in the AM processes, chemical reactions may occur between the powder and contaminants in the building environment, such as oxygen, leading to changes in the chemical composition of the powder [90].
- Taking into account the small size of powder particles in both laser-based AM processes, i.e. 10–20 μm in LPBF and 50–150 μm in DLD, health and safety issues have to be considered, too, when handling metallic powders [91].

Table 1 provides a summary of the advantages and limitations that have been reported for the LPBF and DLD technologies.

It can be stated that achievable accuracy, surface integrity, porosity, relatively poor mechanical and microstructural properties, geometric and material limitations, need for support structures, the high production cost and low production rates are the most challenging issues associated with laser-based AM for building parts from metallic powders. Many of them can be addressed with the use of post-processing operations, such as machining, heat treatments and surface finishing. In the next section, the need for post-processing operations that can be fully integrated with powder-based laser AM processes is discussed.

2 The need for hybrid

As it was already discussed, powder-based laser AM technologies have several shortcomings that represent a significant barrier for their broader use for producing functional parts.

Therefore, almost all AM parts need some post-processing, e.g. machining, heat treatment or surface treatment [93–95]. Hybrid AM, as an integration of AM processes with some post-processing technologies, aim to combine their capabilities synergistically and thus producing functional components with complex geometries, enhanced mechanical properties and improved surface integrity. Machining operations, e.g. turning and milling, heat treatments, e.g. conventional and laser heat treatments, and surface treatments, e.g. shot peening and laser shot peening, are among the most common post-processing operations used in hybrid AM.

Figure 12 shows the advantages of hybrid AM as a combination of additive and CNC machining processes and thus achieving improvements in surface integrity and accuracy. Hybrid AM is also aimed to enable complex shape generation and reduce the waste material and in some cases the lead-time that are associated with machining processes.

In addition to the external defects of AM parts that can be removed by machining, porosity, microstructural defects and residual stresses are other major concerns as they affect the mechanical properties of the parts. Heat and surface treatments have shown to enhance the mechanical properties of AM parts and also to reduce the porosity and improve their microstructural characteristics. Additionally, some of these treatments have shown to reduce the tensile residual stresses of AM parts; hence, their fatigue behaviour is also improved [96–104].

As it was already discussed, the main advantage of AM technologies when compared to conventional manufacturing technologies, such as machining and forging, is that they enable the manufacture of much more complex parts that can incorporate internal cavities while the waste material is drastically reduced [105]. However, these advantages are at the

Table 1 Advantages and limitations of powder-based laser AM technologies

AM process	Technology	Advantages	Limitations	Ref
Powder bed fusion	LPBF	• Higher accuracy and fine details • Fully dense parts • High specific strength and stiffness • Powder recycling	• Powder handling • Need for support structures • High residual stresses • Microstructural and mechanical anisotropy • Size limitation • Low productivity • Limited process modelling and control • Post-processing required • Health and safety issues	[87–89] [78, 84, 92] [45] [75] [77–79] [67, 85] [75, 83] [69, 78] [91]
Direct energy deposition	DLD	• Repair of damaged or worn parts • Flexibility • Functionally graded material generation • Alloy development	• Low accuracy • Rough surface finish • Porosity of parts • Residual stresses • Limitations in printing complex shapes • Process modelling and control • Post-processing required • Health and safety issues	[67, 68] [67, 68] [67, 68] [76] [80] [75] [78, 92] [91]

Fig. 12 Advantages in combining AM and machining processes
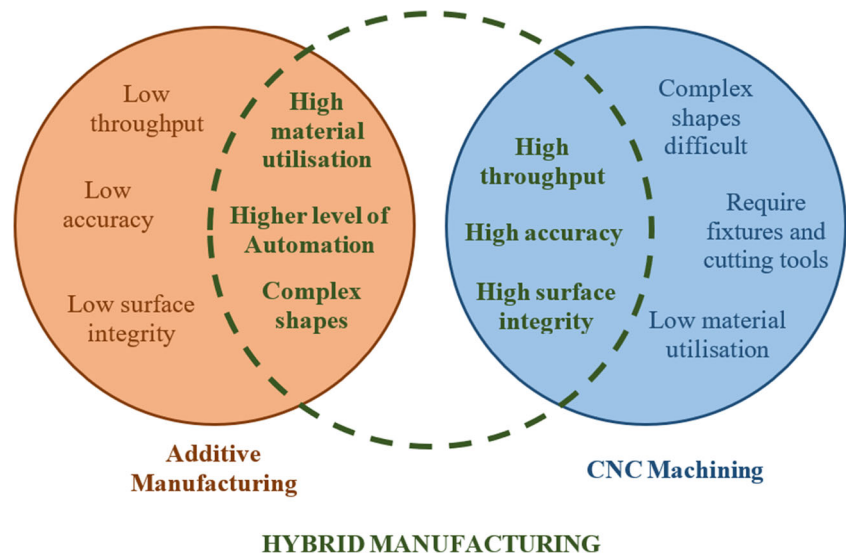
expense of some inherent limitations associated with the layer-by-layer manufacture [106].

As an example of the benefits that hybrid AM can offer by combining powder-based laser AM with post-processing operations, surface roughness values achievable with machining and polishing operations are compared with those achievable with the LPBF and DLD technologies in Table 2. Additionally, the surface roughness values of parts manufactured using Hybrid AM are also included.

As shown in the table, surface roughness values achievable with the LPBF and DLD processes are in the ranges between 5–40 and 30–110 μm, respectively, while in turning or milling, the values decrease to 1–8 μm and 1.5–10 μm, respectively. It is also shown that when post-processing AM parts by employing machining or heat and surface treatments, the roughness is considerably decreased, and values can be reached that are similar to those achievable with conventional manufacturing operations. In addition to surface roughness, dimensional accuracy of AM parts can also be improved and sections with excessive material due to distortions occurring during the AM process can be removed by milling or turning

operations. With regard to heat and surface treatments, it is reported that they can improve part quality, reduce surface roughness and relieve residuals stresses that in turn improves the fatigue life and microstructure of the AM parts [112–121].

It is also worth reiterating that hybrid AM can reduce material waste and lead time and thus reducing the manufacturing costs, too. Regarding the reduction in material waste, by using additive manufacturing as the primary process, near-net-shape parts are generated. Therefore, the amount of material that is removed later in machining operations is much lower than that in the conventional machining processes. This is especially advantageous for the manufacturing of great components employed in the casting and moulding industries. Additionally, in hybrid AM systems, potential human errors can be minimised and even eliminated as all processing steps can be automated by employing CAD/CAM solutions. As a result, functional and end-use parts can be efficiently produced on demand with a minimum lead time.

In the next section, different hybrid AM solutions for producing metal parts are presented.

Table 2 Comparison of roughness values achievable with machining operations, AM technologies and hybrid AM

Manufacturing process	Technology	Roughness Ra (μm)	Ref.
Machining	Turning	1–8	[107]
	Milling	1.5–10	[107]
	Polishing	0.2–1	[107]
Additive manufacturing	LPBF	5–40	[108]
	DLD	30–110	[109]
Hybrid AM	DLD + turning	1.45–1.90	[110]
	LPBF + shot peening	16	[73]
	DLD + laser re-melting	1.5	[109]
	DLD + laser polishing	2	[111]

3 Hybrid AM solutions

Research on combining the capabilities of powder-based laser AM processes with some post-processing operations is reviewed. In Table 3, a summary of the hybrid AM solutions that are analysed and discussed in this section is presented. Different process combinations are reviewed, and their main advantages and limitation are highlighted.

3.1 Hybrid additive/machining solutions

A review of hybrid AM solutions that combine the capabilities of powder-based laser AM technologies with post-processing machining processes is presented in this section. In particular, in such hybrid solutions, near-net-shape components are first produced by LPBF or DLD technologies and then they are post-processed by employing machining operations, e.g. turning or milling. The machining operations can be conducted once the AM process is completed, as a finishing process, or can be alternatively applied after the consolidation of a given number of powder layers.

Figure 13 extracted from the work by Foster et al. [62] shows an example of the improvement that can be obtained in the surface finish of additively manufactured components by post-processing through machining operations.

Different approaches for combining seamlessly and synergistically the capabilities of powder-based laser AM technologies with post-processing machining processes have been implemented. In 2007, Liou et al. [77] reported a hybrid solution that integrates DLD and machining processes into a 5-axis single setup for producing metallic parts. First, the authors studied the necessity for support structures during the powder deposition process and thus determining whether the

DLD process could be conducted without them by changing the part orientation. Then, based on the findings of this investigation, an approach for partitioning part models into subparts was proposed that eliminated the need for support structures when different processing positions in a 5-axis machine were used for each subpart. The pre-processing of each subpart model, i.e. its slicing, was carried out separately and thus using optimum DLD conditions for processing the subparts.

According to Jones et al. [135], the productivity of AM technologies is typically one order of magnitude lower than that of CNC machining. Therefore, a hybrid AM solution was proposed that combines the capabilities of DLD and CNC machining processes into a single multi-axis setup and thus improving both surface integrity and productivity. In this work, the tool changer solution was proposed, too (see Fig. 14) that allowed a laser cladding head and different cutting tools to be used in the same system.

The machining operation can be applied not only for finishing metal AM parts but also in alternation to the deposition of layers in hybrid AM solutions. In this way, Karunakaran et al. [7] reported a hybrid AM system in which near-net-shape structures were first produced by using a DLD head, i.e. a welding head, mounted on a table and subsequently machined to net shape. As the deposition was carried out in the form of weld beads, the surface of the deposited layer was uneven due to the scallops and the developed thin oxide layer. Thus, such uneven deposition of layers can have a cumulative effect on the accuracy of the component in the Z direction and therefore this shortcoming was addressed by face milling each layer to the required slice thickness. So, each subsequent weld-deposition was conducted on a pre-machined surface and thus having good quality welds and build metal parts consistently. A similar hybrid AM solution was proposed by

Table 3 Summary of hybrid manufacturing processes

| Hybrid manufacturing	AM technology	Post-processing	Advantages	Limitations and challenges	Ref.
Additive manufacturing + machining	LPBF	Machining	Complex geometries and good surface finish	Needs part inspections, software integration, parameter optimisation, oxidation (out of chamber AM). Undercuts cannot be machined.	[77, 79]
	DLD	Machining	Productivity gains and good surface finish		[10, 122, 123]
Additive manufacturing + heat treatment	LPBF	Laser re-melting	Improved microstructure, reduced residual stresses and surface roughness and enhanced surface properties	Needs parameters optimisation.	[124–131]
	DLD	Laser re-melting	Smooth surfaces and isotropic topographies	Needs parameters optimisation	[132]
Additive manufacturing + surface treatment	LPBF	Laser polishing	Reduced surface roughness	Process optimisation is required to avoid oxidation	[133]
	DLD	Laser polishing	Reduced surface roughness	Results are highly dependent on laser energy	[111]
	DLD	Peening	Refined microstructure and beneficial compressive residual stresses	Integration of processes in the same machine.	[134]

Fig. 13 Surface finish of samples in (**a**) as deposited and after machining states [62]

As deposited

After machining
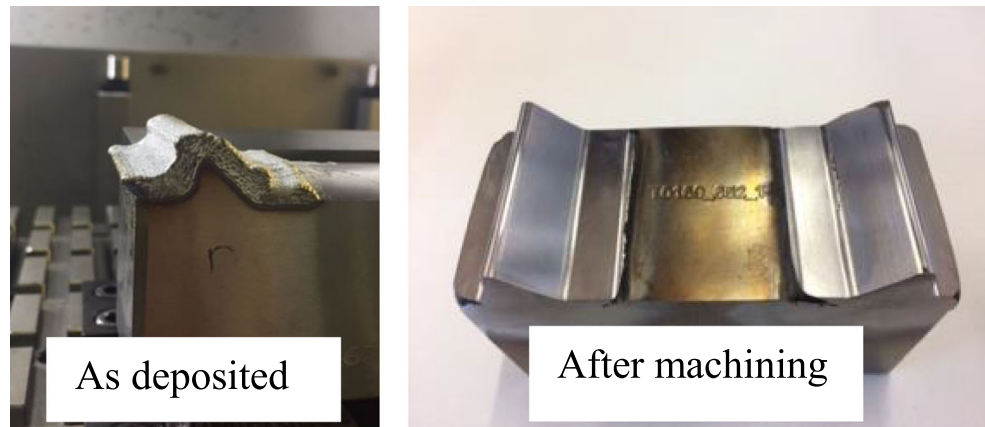
other researchers but it was combining LPBF with precision milling in a single setup [79]. In particular, the parts were manufactured layer by layer by conducting LPBF and machining steps sequentially onto a substrate clamped on a work-table as shown in Fig. 15. By employing this hybrid AM/machining process, complex internal structures, such as cooling channels, were produced. The manufacture of 18Ni steel parts was reported, and their microstructure and hardness were analysed and compared with those achieved on parts produced by a standalone LPBF system and other methods. It was reported that the hybrid samples showed density higher than 99%, fine microstructure and higher hardness than the result obtained on parts fabricated using the standalone LPBF process.

The development of a hybrid multi-tasking machine tool was reported where a DLD head was integrated with turning and milling capabilities into a hybrid solution for reducing the manufacturing time and the total in-process time [136]. This hybrid manufacturing platform was implemented into a commercially available machine tool, Integrex i-400 AM, to address the specific requirements in the small-lot production of difficult-to-cut high-hardness materials for applications in aerospace, energy, medical device and tool-making industrial
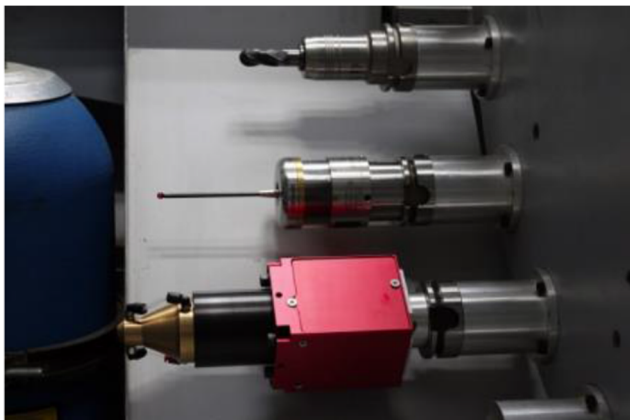
**Fig. 14** Image of the cladding head, touch probe, and end mill co-existing in the tool changer [135]

sector. Figure 16 depicts an application of this hybrid AM solution for producing a bi-metal part with a stainless steel substrate and deposited Inconel 718 on it.

Another approach for creating hybrid AM solutions is the integration of AM technologies with pre-processing and post-processing processes into multi-setup manufacturing platforms through the use of common work holding systems. The design and implementation of such modular work holding system were reported for integrating the LPBF process into AM enable process chains [122].

It is important to stress on differences between single- and multi-setup hybrid AM solutions, especially former execute AM and post-processing operations in one machine tool that later addresses fixturing and position issues in moving the components along a given AM enabled process chain. The multi-setup hybrid AM enabled manufacturing platforms to address some of the limitations of single setup ones. In particular, the AM and machining modules integrated into multi-setup solutions can be optimised independently to address the specific performance requirements of an individual process rather than the requirements of all integrated manufacturing processes into a single setup [97]. So, the fundamental differences in the physical characteristics of integrated processes would not increase the engineering complexity of such multi-setup manufacturing solutions unnecessarily and therefore their overall cost would not increase considerably, compared to the single setup systems. Other important advantages of the process chain approach in combining AM capabilities with other processes is that it can deliver much higher productivity due to the parallel utilisation of the integrated operations and also because it provides flexibility to synchronise the throughputs of each manufacturing module [137].

The modular work holding system reported in [122] was later employed by Badhuri et al. [82] to investigate the surface integrity, microstructure and mechanical properties of hybrid AM aluminium parts produced by employing LPBF followed by some machining operations. In another research, the same work holding system was deployed to build LPBF structures on top of metal injection moulded (MIM) preforms and thus

Fig. 15 Schematic description of the hybrid LPBF/machining process [79]. The figures are reused under the Creative Commons CC-BY licence
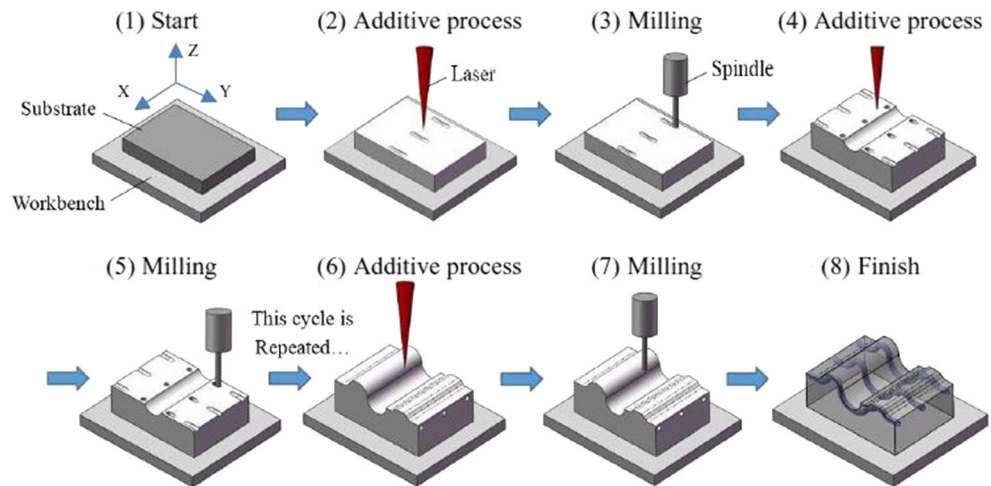
producing small series of hybrid 316L stainless steel components [138]. The mechanical properties and interfaces of such hybrid MIM/LPBF components were investigated and it was reported that they were similar and even better than those of monolithic MIM parts while conforming fully to the ASTM standards for 316L stainless steel parts.

A similar multi-setup approach was employed by Boivie et al. [123] to combine the LPBF process with 5-axis milling and thus producing injection moulding tools. In particular, the implemented hybrid AM solution enabled the manufacture of conformal cooling channels in complex cavities that led to the production of higher quality mouldings and also allowed the injection moulding cycle time to be reduced, significantly.

## 3.2 Hybrid additive/surface treatment solutions

The hybrid AM/surface treatment solutions are similar to hybrid AM/machining ones as the processes are carried out sequentially either on single or multi-setups. In particular, in the latter, near-net-shape components are produced employing an AM process and then they are treated to improve their microstructure and mechanical properties and also to reduce the residual stresses. While in the former, treatment can be applied in the same AM setup after the deposition of layers [139, 140]. In this review, laser re-melting (LR), laser peening and laser polishing are considered as surface treatments solutions to improve the properties of AM components.

Laser re-melting (LR) is a process that has attracted a growing interest from researchers and industry. LR has shown to decrease porosity and improve the microstructure of the AM parts (see Fig. 17).

Huang et al. [125] defined "laser re-melting" as scanning strategies that have more than one laser beam pass for each LPBF layer. The second and any further beam passes aim to increase the material densification and also to improve surface integrity and microstructure. A similar approach was applied

by Lamikiz et al. [126], however, this time sequentially as a hybrid multi-setup solution. In particular, a laser beam was employed to melt a microscopic layer on the surfaces of LPBF parts that after its re-solidification made the LPBF surfaces smoother. An 80% reduction of the average surface roughness was achieved by applying this laser treatment method. More recently, Yasa et al. [127] studied the influence of different laser processing parameters, i.e. scan speed, scan spacing and number of re-melting scans, on porosity, surface roughness and microhardness of AISI 316L stainless steel and Ti6Al4V parts produced by the LPBF process. In all experiments, the use of re-melting scans improved surface integrity and properties of produced parts. Considering the parameter range employed in their work, authors observed that higher re-melting scan speed combined with low laser power showed low porosity values. Additionally, in low-energy input tests, no relevant change in porosity was observed when increasing from one to three re-melting scans. However, as the energy input was increased and, at the same time, the number of re-melting scans was also increased, the porosity increased significantly. In another research, the same authors investigated the effect of laser re-melting when applied only to the last layer of LPBF AISI 316L parts and again a 90% improvement of the surface roughness was reported [128]. Yang et al. [129] studied the changes in microhardness and microstructure after laser re-melting of LPBF samples, too. The results showed that laser re-melting had refined the material microstructure, i.e. had reduced the grain sizes, and also homogenised the material composition that improved microhardness of the treated samples. Wei et al. [130] carried out a study on the influence of the number of re-melting scans on porosity, roughness and residual stresses. It was reported that the scan number did not affect porosity and roughness. However, the residual stresses increased when one re-melting scan was used and then decreased after two or more re-melting scans.

Fig. 16 Application example of the hybrid multi-tasking machine tool, Mazak INTEGREX i-400 AM [136]. The figures are reused under the Creative Commons CC-BY licence

Setting a substrate   Machining   High Speed LMD   Fine LMD

Machining   Laser marking
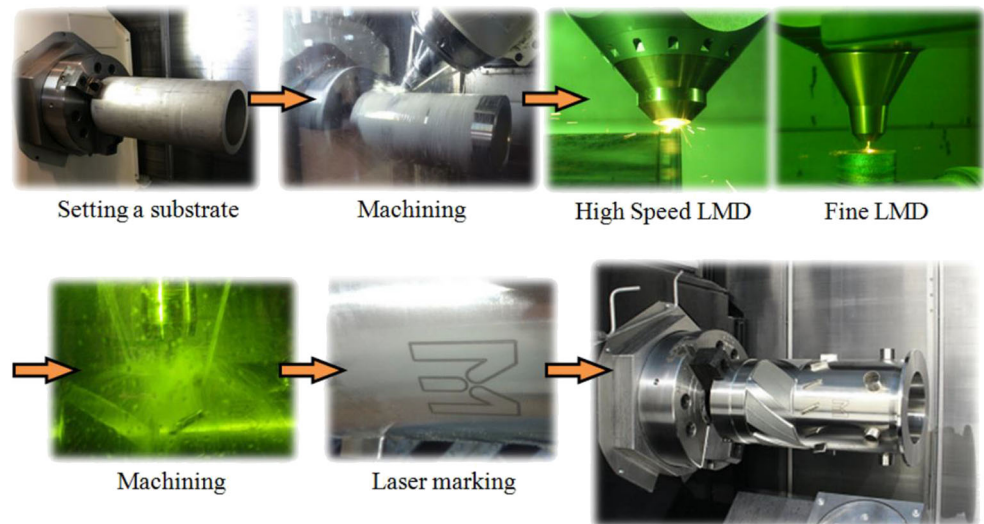
In another research, Yu et al. [131] studied the influence of using different scanning directions during the LPBF and re-melting processes, on roughness and porosities of produced parts. It was reported that the scan strategies investigated in this research led to the same roughness decreasing trend. However, the use of different scan directions had affected the porosity of produced LPBF parts.

Laser re-melting has also been employed for post-processing DLD parts. Bruzzo et al. [132] investigated the surface integrity improvements of thin-walled parts after laser re-melting. It was reported that, when suitable re-melting parameters were employed, a smooth surface with isotropic topographies was obtained. Recently, Roehling et al. [142] investigated in situ laser diode annealing integrated into a LPBF system for reducing the resulting residual stresses. It was reported that such integrated heat treatment can reduce the resulting residual stresses in 316L stainless steel parts by 90% without grain growth or recrystallisation, and with only minor changes to the solidification structure.

Peening (also known as shot penning) is another hybrid AM/surface treatment approach that can be used to improve the surface finish and mechanical behaviour of metallic AM parts (see Fig. 18b).

In particular, it has shown to harden and strengthen the surfaces of AM parts by generating compressive residual stresses. As a consequence, favourable mechanical properties are created on treated surfaces that can increase their fatigue life (see Fig. 19) and wear resistance and thus delaying the initiation and propagation of cracks. In the work by Hackel et al. [100], authors show that laser peening can improve the fatigue lifetime of components more than 20 times comparing to that of the untreated part.

Wang et al. [134] studied the effects of in situ ultrasonic impact peening on Inconel 718 parts produced with the DLD technology. It was reported that the ultrasonic impact peening

enabled the generation of high-quality metal parts with refined microstructure on their treated surfaces. In addition, the residual stresses of the treated surface were reduced by generating beneficial compressive stresses.

Another surface treatment process that can be used to reduce the surface roughness of AM metal parts is laser polishing (see Fig. 18c). Similar to laser re-melting, this post-processing technology melts the external surface asperities of the AM part and thus improves surface integrity. Dadbakhsh et al [111] reported that the surface roughness of DLD Inconel 718 samples was significantly improved after a laser polishing scan with the laser integrated into the DLD head, especially roughness values decreased down to approximately 2 μm. However, it was noted that the results were highly dependent on the applied laser power during the polishing scans.

4 Commercial hybrid manufacturing systems

Table 4 lists the commercially available hybrid systems that gives a general overview of the current status with the take-up of this technology by industry and also their general technical specifications for comparison purposes [144].

In addition to the hybrid machine manufacturers listed in Table 4, there are other companies that have developed flexible solutions to transform machining centres into hybrid machines capable of combining additive and subtractive technologies. For example, 3D Hybrid [155] has developed wire arc, laser and cold spray deposition heads that can be integrated into CNC machines. Fabrisonic [156] patented an ultrasonic AM print-head that can be integrated into any 3-axis machining centre to convert it into a hybrid AM solution. Finally, Hybrid Manufacturing Technologies [157] has developed a range of tool heads for inspection, machining and DLD

Fig. 17 Benefits of LR. **a** Improvement of surface morphology [120]. **b** Decrease of part porosity [141]

(a)

(b)
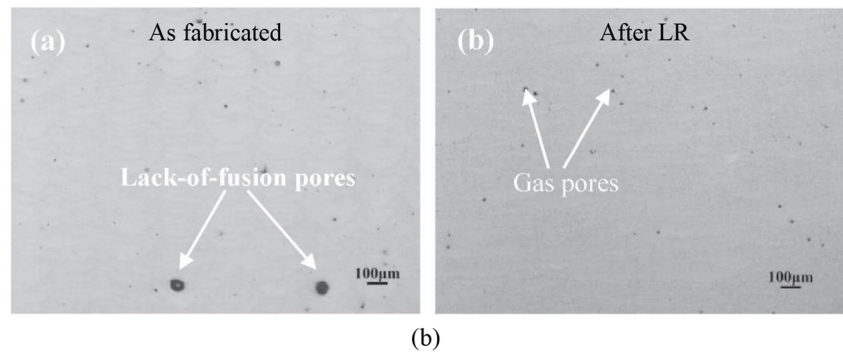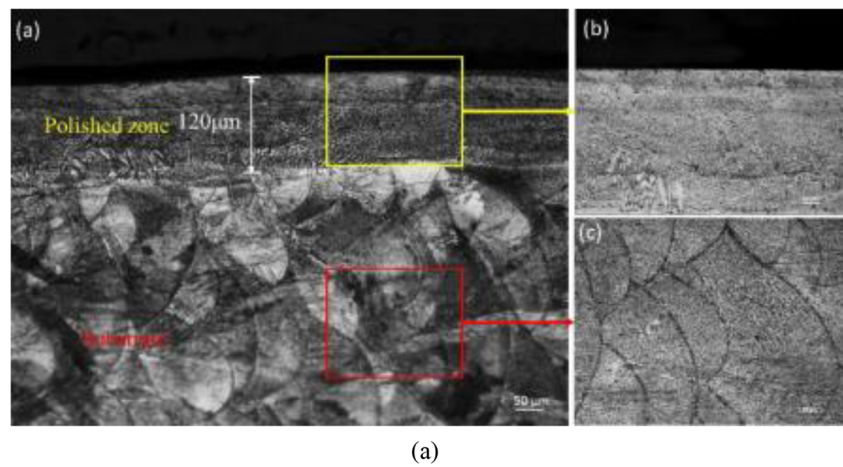
operations that can be integrated into machining centres and thus creating ad hoc hybrid AM solutions.

It is worth noting that any LPBF or DLD system available currently on the market can also conduct in situ heat or surface treatment operations with their integrated laser sources. As discussed in Section 3.2, these treatments have proved to improve the mechanical properties, microstructure and surface quality of metal AM components. Therefore, any of those systems can be considered potentially as hybrid AM solutions as AM and the post-processing operations can be carried out in a single setup/machine. In addition, the LPBF machine developed by Additive Industries MetalFAB1 [36] offers an

integrated furnace for heat-treatment and therefore can be considered a hybrid AM system.

Apart from the hybrid machined presented above, robotic solutions can also be an alternative for hybrid additive manufacturing systems. These solutions are usually based on DED processes conducted by a robotic arm that is integrated into a machining environment. In fact, robot-assisted additive manufacturing approaches have been widely analysed lately as they offer the possibility to accomplish multi-axis additive manufacturing that can be integrated into different manufacturing environments [158]. As for the hybrid additive manufacturing of metals, Kimpenis et al. [159] presented

(a)   (b)   (c)
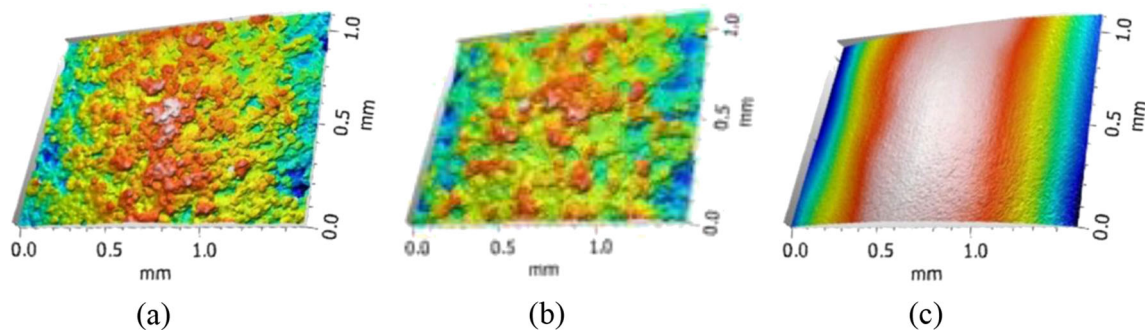
Fig. 18 Effect of surface treatment on additively manufactured components. **a** As-fabricated surface topography. **b** Improvement of surface finish through laser shot peening. **c** Through laser polishing [143]

Table 4 General specifications of commercially available hybrid system

Company	Combination of processes	Hybrid machine	AM technology	Post-processing	Max. part size	Max. laser power	Laser spot diameter	Advantages	Ref.
DMG MORI	DLD + machining	LASERTEC 65 3D	DLD	5-axis milling	Ø 500 mm 400 mm height	2500 W	3 mm–1.6 mm	Multi-material	[145]
Yamazaki Mazak	DLD + machining	Integrex i-400 AM	DLD	5-axis milling and turning	Ø 658 mm 1519 mm length	1000 W	-	Multi-tasking Multi-material	[146]
Matsuura	LPBF + machining	LUMEX Avance-25	LPBF	Milling	600 × 600 × 500 mm	500 W – 1000 W	-	First in developing LPBF+ SM	[147]
Optomec	LENS + machining	LENS print engine	DLD	3 + 1-, 3 + 2- and 5-axis milling	800 × 600 × 600 mm	3000 W	0.67, 2 and 3 mm	Controlled atmosphere Up to 4 additional powder feeders	[148]
Sodick	LPBF + machining	OPM350L	LPBF	3-axis milling	350 × 350 × 350 mm	500 W – 1000 W	--	Material recovery system	[149]
Ibarmia	Laser cladding + machining	ADD+ PROCESS	DLD	5-axis multitasking (mill and turn)	-	3000 W	-	Different working envelops available	[150]
Hamuel Rechenbacher	Laser cladding + machining	HSTM-1000	DLD	5-axis milling	-	-	-	Fexibility 3D inspection Deburring/polishing	[151–153]
Additive industries	LPBF + heat treatment	MetalFAB1	LPBF	Heat treatment	420 × 420 × 400 mm	500 W	-	Up to 4 lasers can be integrated	[154]

recently the HydraX robot that can be integrated in almost any type of machine and enables to combine multiple processes in a single machine. It is worth noting that almost all components in this robotic arm were generated by AM processes.

5 Applications of hybrid manufacturing

Taking advantage of the flexibility offered by AM, hybrid AM solutions enable the manufacture of complex parts with geometries/structures that were previously unachievable. Parts' repair is among the applications that have attracted a significant industrial interest due to the direct economic benefits it can bring in repairing high-value components. The combining AM with post-processing operations in a single or multiple setups enables the repair of damaged or worn parts and thus extending the parts' life span and potentially to avoid the need to replace them with new ones. Additionally, AM processes enable the use of different materials and thus producing multi-material and functionally graded material (FGM) components, which is another very attractive application for hybrid AM solutions.

In this section, a review of the most relevant and high-impact applications of hybrid AM solutions reported in the literature is presented. The feasibility of applying a hybrid AM approach in producing complex geometries, part repairs and the manufacture of FGM parts is discussed. In addition, the advantages and challenges associated with the deployment of this approach for producing parts that can address the specific requirements in different industrial sectors are discussed.

5.1 Manufacturing of complex end-use geometries

Hybrid AM solution can combine the capabilities of metal AM technologies with those of different post-processing processes to produce end-use parts. One of the main advantages that AM processes provide is the flexibility and freedom to produce complex geometries with internal cavities that were impossible to achieve with conventional manufacturing processes only. Collision avoidance is one of the biggest issues in generating complex geometries using hybrid AM solutions. In particular, tool accessibility must be maintained over the processed surfaces when post-processing them through various machining operations, and therefore, this issue has to be taken into account during the process design/planning stages. In addition, to minimise any material wastage the machining strategies and part positioning for each post-processing operation should be optimised.

Liou et al. [77] reported a hybrid AM approach for the production of complex parts by integrating a DLD device into a multi-axis CNC machine. The results showed that the need for support structures during the AM process could be avoided by selecting the optimal part positioning and inclination

angles during the DLD process. A process planning method was proposed in this research for the DLD process that included the following steps: (1) selection of part orientation, (2) part partitioning into subparts for creating them with the same building direction, (3) determining the DLD building sequence and (4) verifying the machinability of built subparts and thus avoiding any collisions during their post-processing. Recently, Chen et al. [160] proposed a new process planning when a hybrid AM approach was utilised. Their research was motivated by the need for proper planning of manufacturing sequences and thus ensuring collision avoidance during both DLD and machining operations. Their research was mainly focused on the application of hybrid AM solutions for producing complex geometries, such as aero-engine blisks and gears, among others. Especially, a model was proposed for simulating the relative in-process movements of workpiece and cutting tools and DLD heads, and thus determining the optimal sequence of tasks in producing complex shapes without collisions.

Sodick [149] machine manufacturer has developed a hybrid AM machine that integrates LPBF and machining operations for the generation of complex end-use parts. Components that can be manufactured with their hybrid OPM series machine are provided in Fig. 20 and Fig. 21. Figure 20 shows samples with internal cavities and complex geometries that were produced by combining LPBF and milling operations, i.e. (a) a sample with a spiral-shaped cooling channel with machined external surfaces, (b) a sample with a high aspect ratio rib; (c) a twisted topologically optimised cage tower with a machined upper surface; and (d) a punch with a narrow high aspect ratio slot.

Figure 21 shows examples of components with internal cooling channels and external complex geometries, i.e. an EV connector, a switch box and a duct shape core, that were not possible to produce with machining operations only, but

they were successfully manufactured with the OPM Series machine.

Matsuura [163] has developed a hybrid AM machine that integrates LPBF and machining operations into a single processing setup as shown in Table 4. Figure 22 shows examples of moulds and components that were manufactured using the Matsuura hybrid AM system.

Finally, Mazak [146] has developed a hybrid AM machine that integrates a DLD head into a multi-tasking machine tool with the technical characteristics given in Table 4. Figure 23 shows product examples that were produced employing this hybrid AM solution.

5.2 Repair of metallic parts

The development of metal AM processes has enabled the repair of worn or damaged metallic parts and thus increase their life span and also minimise the need for re-manufacturing. Such capabilities are of special interest in the application areas for high-value components, e.g. in tooling applications where saving in lead time and cost can be made by repairing the damaged dies and moulds [165]. However, taking into account the tight tolerances that are typically required in tool-making, aerospace and automotive industries and also considering the limitations of stand AM systems, hybrid AM solutions have emerged as a viable alternative for repairing parts in these industrial sectors.

As it was already stated, there is significant interest in using hybrid AM solutions for tool repair. Ren et al. [166] reported an alternative approach for die repair that was combining DLD with CNC machining. The repair of most common die damages with such hybrid system was studied, especially dies that were worn out or damaged. The bonding strength of deposited material in such repaired dies was analysed and it was concluded that it was higher when compared with dies

Fig. 19 Fatigue lifetime improvement through laser peening (LP) and shot peening (SP) [100]
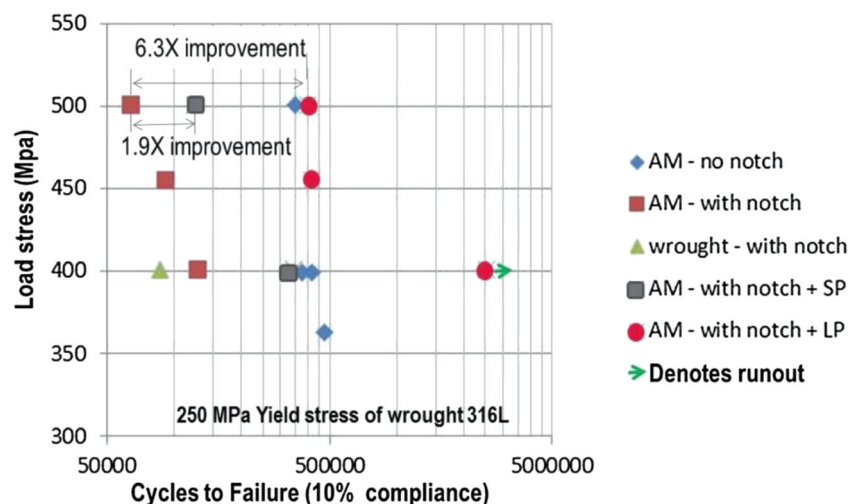
Fig. 20 Hybrid AM parts produced with Sodick's new OPM250L machine that combines LPBF with milling operations [161]

(a) (b) (c) (d)
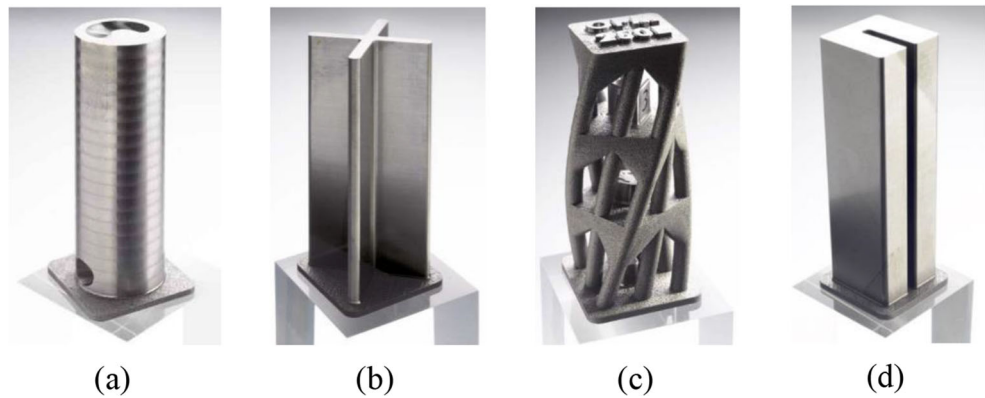
repaired with the conventional welding methods. Figure 24 depicts the stages in the die repair process.

Bennet et al. [167] investigated the capabilities of a DLD head when integrated into a hybrid AM solution when applied for repairing automotive dies. First, the damaged areas of the die were removed through machining and then they were rebuilt with the DLD process. H13 dies were repaired with the hybrid process and also with the conventional TIG process for comparison. It was stated that the repaired die with the hybrid AM process had the same life span as that processed with the conventional TIG method. Recently, Zhang et al. [168] reported a hybrid process that combined reverse engineering, pre-repair processing, AM and material testing. The proposed method was applied for the repair of a H13 die with different types of defects. First, worn out sections were scanned to re-create the 3D model of the die. Then, these sections were machined out and heat treated to prepare them for the AM process. Next, the worn out sections were restored with the DLD process and finally their microstructure and mechanical properties were analysed. The results showed that a strong bonding was achieved between the deposited material and the pre-machined die. In another research, Foster et al. [62] investigated the feasibility of combining the DLD technology with finishing machining into a hybrid AM system for repairing dies by cladding Stellite cobalt-based alloy onto the worn out areas. The repaired die was subjected to hot

forging, and it was reported that the die performance was the same or better when compared with that of a standard die. In particular, it was noted that the adhesive and abrasive wear modes of the repaired die performed better than the standard one.

Figure 25 shows common defects that appear in dies and moulds that could be repaired by employing hybrid AM solutions.

Repair of other high value components by using hybrid AM approaches was also reported in the literature. Le et al. [171] proposed a process planning approach for combining AM with subtractive operations. The methodology enables the repair of parts with high accuracy and thus avoiding the material recycling stage. The workflow for conducting a part repair with this hybrid method includes the following three steps: (1) a pre-processing stage, at which an inspection of the worn-out part is conducted; (2) a processing stage, at which AM, subtractive, inspection and heat treatment operations are combined; and (3) a post-processing stage, at which the final inspection of the part is conducted.

Praniewicz et al. [172] investigated a hybrid AM solution for DLD of Stellite alloy on 410 stainless steel substrates. The deposited material on the workpieces was analysed to assess the effect of process parameters on their internal and external porosity, microstructure and surface roughness. In particular, preliminary experiments were conducted first and thus

Fig. 21. Applications of a hybrid LPBF and machining solution developed by Sodick. **a** EV connector. **b** Switch box. **c** Duct shape core [162]

(a) (b) (c)
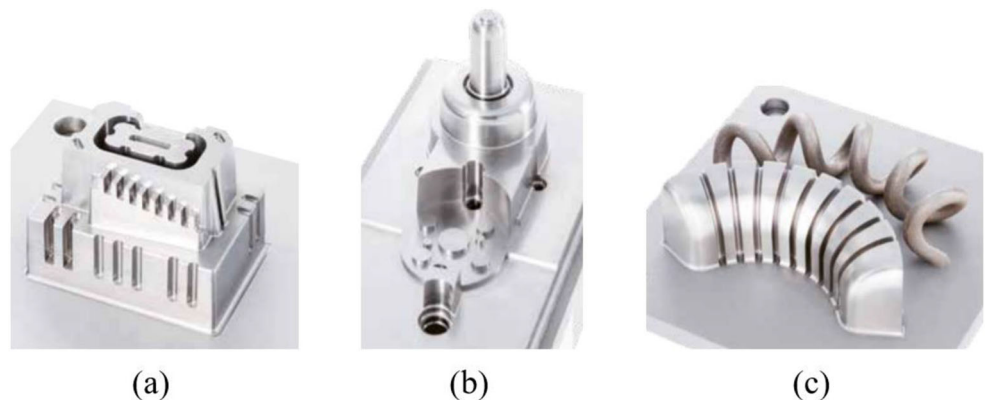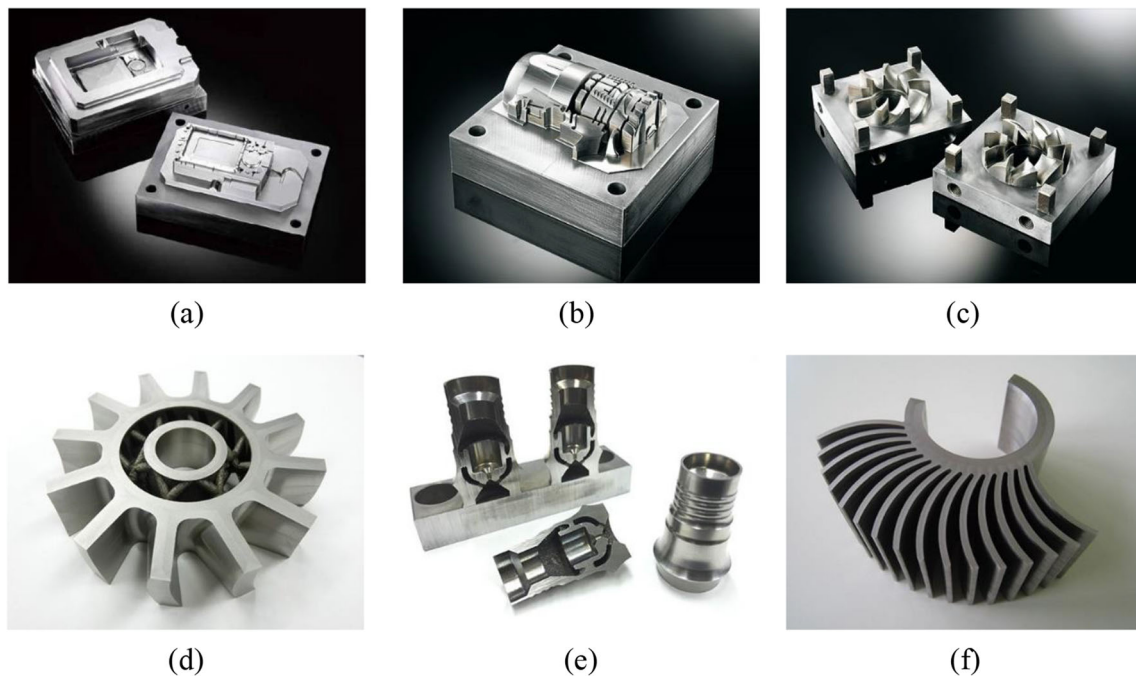
Fig. 22 Hybrid AM applications by Matsuura Lumex Series Hybrid machine, i.e. mould tools for digital camera (**a**), electric driver (**b**) and the manufacture of a fan (**c**); and products for blisks (**d**), jet engine nozzles (**e**) and cooling fins (**f**) [163]

optimising the process parameters. Then, a disc-shaped cylinder was manufactured with the optimised parameters. It was reported that in spite of the fact that some areas were inspected, the DLD process led to some flaws in the part, including surface voids and internal cracking.

Figure 26 shows examples of repaired parts for different industry applications where hybrid AM solutions were applied.

5.3 Functionally graded materials

The DLD technology provides capabilities for depositing different materials on components and thus enabling their manufacture from so-called functionally graded materials (FGM) and specially tailored alloys. FGM are characterised by variations of materials or their microstructures across the deposited sections and thus properties and functionality can be varied at different locations within the part volume [173]. The gradual changes of constituents along certain direction provide graded macroscopic and microstructures properties, such as hardness, wear resistance, corrosion resistivity, etc. In fact, some of the hybrid AM system list in Table 4 have the capabilities for multi-material deposition. In particular, Lasertec 65 3D from DMG Mori and Integrex I-400 AM from Yamazaki Mazak allow multi-material depositions and thus building FGM sections and parts. Many research groups have analysed FGM parts produced employing different hybrid AM solutions [174–182].

Figure 27 shows a schematic diagram of FGM [183] combining Haynes 282 material with progressively increasing amount of SiC. As depicted, the composition and properties of the materials can be changed from one end to another along the Z-axis. However, depending on the applications, there might also be changes from centre to end [174].
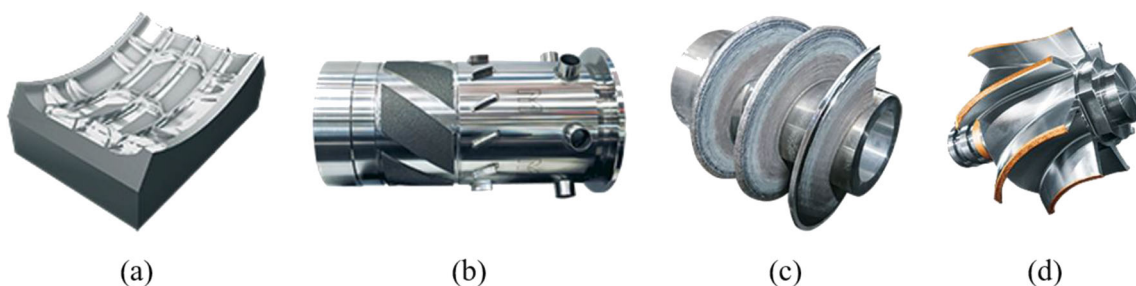
Fig. 23 Hybrid AM applications of the Mazak Integrex i-400AM system. **a** A mould insert. **b**, **c** General machinery. **d** Surface coating added to an impeller [164]
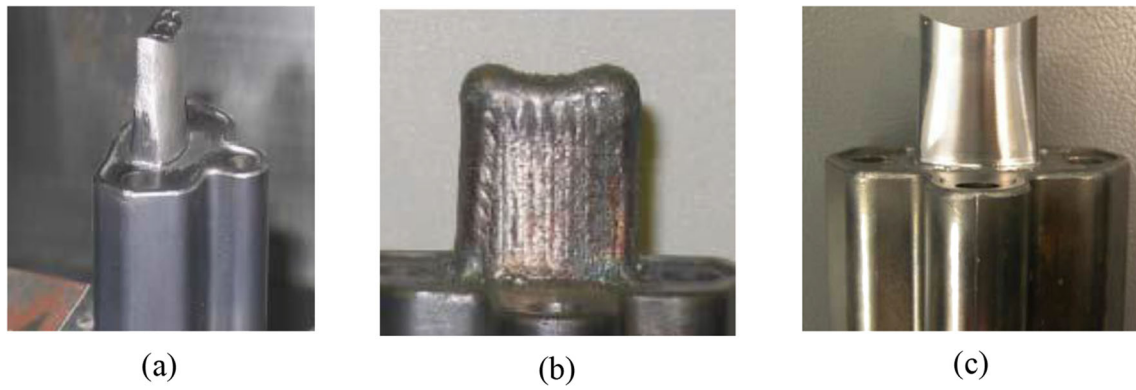
Fig. 24 A die core repair with a hybrid AM solution. **a** A worn out die before the repair. **b** After the DLD operation. **c** After the machining operation [166]

Figure 28 shows an example of an FGM application, in which different materials are employed for the substrate (steel) and for the deposition (copper).

Liu et al. [175] deposited a TiC/Ti composite employing the DLD process and graded the composition from 100% TiC to almost 95% Ti across the part. The DLD head consisted of four coaxial nozzle around the laser beam and two powder feeders with controlled deposition rates were used to deliver Ti and TiC powders. Results showed that the DLD system produced successfully FGM samples while prevented the crack formation. Li et al. [176] used again a DLD system to create FGM by gradually varying the composition from

Ti6Al4V to SS316. A transition composition route was employed, i.e. as follows Ti6Al4V → V → Cr → Fe → SS316, with the aim of avoiding the development of intermetallic phases between Ti6Al4V and SS316 and thus producing a thin wall sample. A gradual transition in composition was achieved to produce a structure with no cracks or intermetallic phases between Ti6Al4V and SS316 alloys. Chen et al. [177] deployed the DLD process to deposit 316L/Inconel 625 FGM. Initially, the composition was 100% 316 L stainless steel and then gradually it was changed to 100% Inconel 625. FGM parts with a homogenous microstructure were produced while the material composition was varied continuously. A good
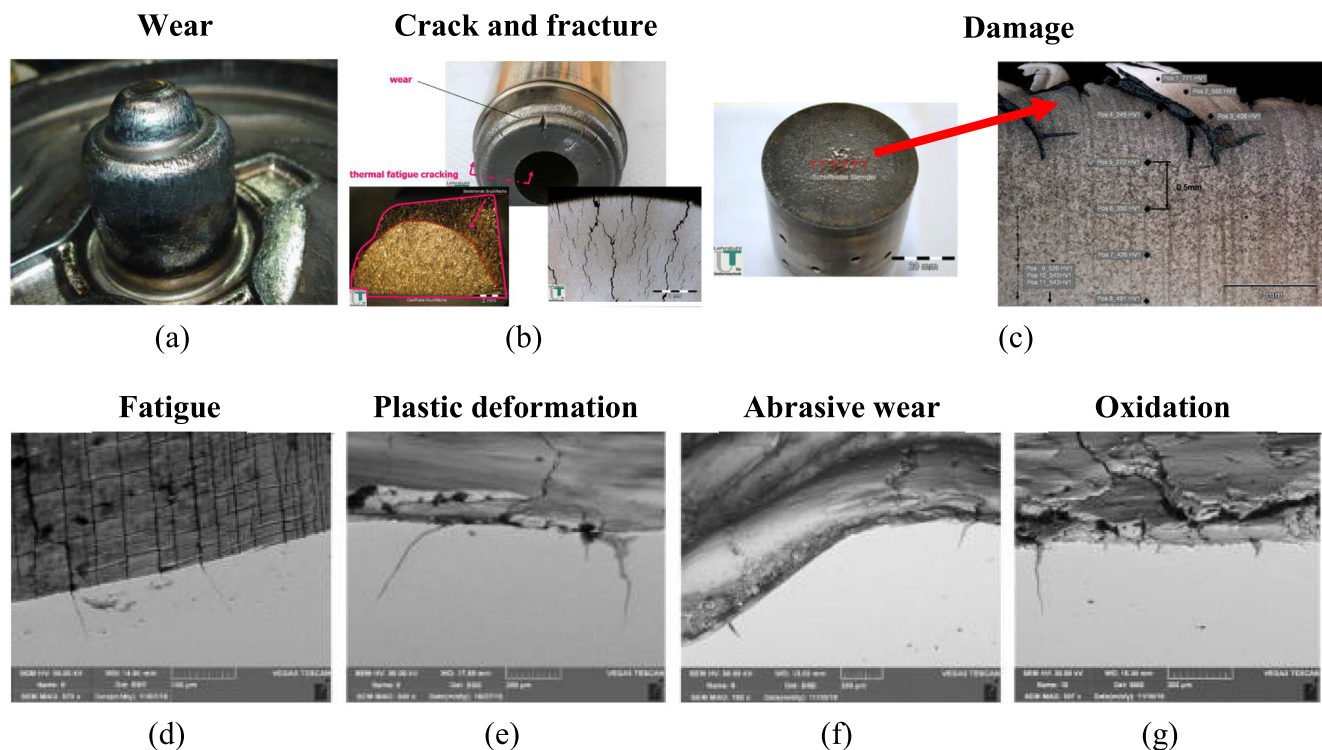
Fig. 25 Defects in dies and moulds that could be repaired by employing hybrid AM solutions [169, 170]

Fig. 26 Parts repaired with hybrid AM solutions. **a** A turbo impeller. **b** Sheet metal mould [164]
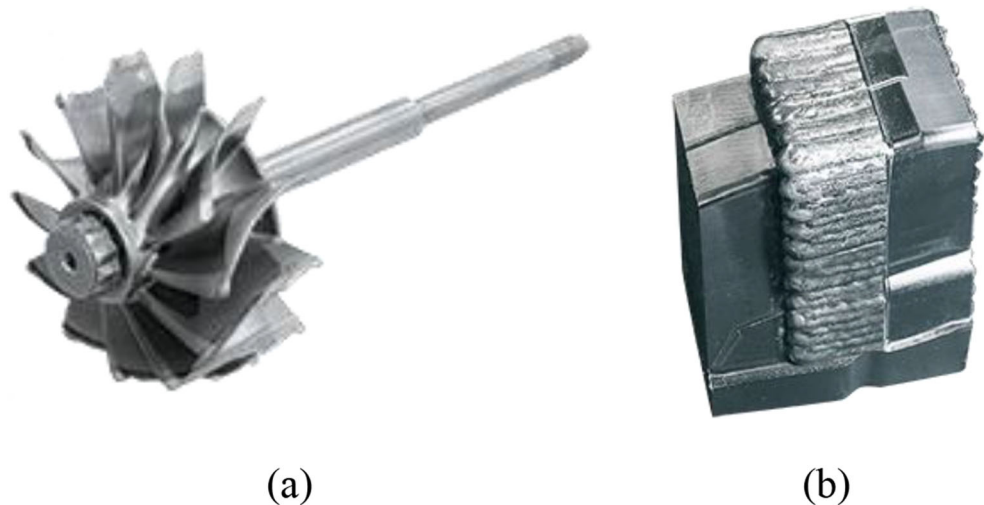
linear gradient between Fe and Ni was achieved as a result of the good diffusion and the strong bonding between the deposited layers.

The FGM concept has been applied in several application areas, e.g. to produce transport systems, energy transfer systems, cutting tools, machine elements, optics, biomedical components, etc. FGM are of special interest for producing structural parts that require combinations of characteristics that cannot be found in a single material, e.g. hardness with toughness, or chemical inertness with toughness [178]. Table 5 includes some potential FGM applications with their respective industrial sectors.

FGM have a wide range of applications, and hybrid AM solutions are important enablers for producing FGM parts.

Especially, the hybrid AM route can enable the manufacture of end-use parts with high surface quality, dimensional accuracy and tailored mechanical properties.

6 Challenges of hybrid additive manufacturing

Hybrid AM solutions can address many of AM limitations and challenges; however, they have their own specific challenges that limit the broader use of this promising technology by industry. This section discusses the main challenges of the hybrid AM technology for producing metal parts.

Fig. 27 A schematic representation of functionally graded materials [183]

Layer 16	85 %Haynes 282 + 15 % SiC
Layer 15	86 % Haynes 282 + 14 % SiC
Layer 14	87 % Haynes 282 + 13 % SiC
Layer 13	88 % Haynes 282 + 12 % SiC
Layer 12	89 % Haynes 282 + 11 % SiC
Layer 11	90 % Haynes 282 + 10 % SiC
Layer 10	91 % Haynes 282 + 9 % SiC
Layer 9	92 % Haynes 282 + 8 % SiC
Layer 8	93 % Haynes 282 + 7 % SiC
Layer 7	94 % Haynes 282 + 6 % SiC
Layer 6	95 % Haynes 282 + 5 % SiC
Layer 5	96 % Haynes 282 + 4 % SiC
Layer 4	97 % Haynes 282 + 3 % SiC
Layer 3	98 % Haynes 282 + 2 % SiC
Layer 2	99 % Haynes 282 + 1 % SiC
Layer 1	100 % Haynes

Table 5 Examples of FGM applications in different industries

Industry	Application	Reference
Biomedical	Femoral stem protheses Dental implant	[179–181]
Energy industry	Heat exchange panels	[182]
Automotive	Engine cylinder liners Combustion chambers	[182]
Aerospace	Rocket nozzle Wings	[182]

Strong et al. [185] reported a survey among traditional manufacturers that highlighted the open issues associated with the access of metal AM systems, process engineering, tooling requirement (tool access) and part quality control. In addition, it was noted that hybrid processes combining AM with machining technologies are not yet applicable in many industrial sectors due to the size limitations of AM systems.

6.1 Materials and machinability

The machinability of metal AM parts is one of the main open issues that prevent the broader take up of hybrid AM solutions. In addition, the intrinsic characteristics of metal AM processes affect directly the machinability of the compacted powder through laser-material interactions. In particular, during material deposition operations, parts are subjected to high thermal gradients, i.e. high heat and cooling rates, that lead to a higher strength and hardness of the compacted powder and

consequently to higher cutting forces and tool wear rates [186]. Milton et al. [187] reported that the increase of cutting forces was possibly due to microstructural discontinuities of AM components, which entailed higher wear rates and lower tool life.

The most common materials and alloys employed in metal AM processes can be clustered into stainless steel alloys (316L, 17-4PH, etc.), nickel-based and cobalt-based superalloys (Inconel 625, Inconel 718, CoCrF25, etc.), titanium alloys (Ti6Al4V, CPTi, etc.) and aluminium alloys (AlSi10Mg, etc.). Some of these alloys on their own are considered difficult-to-machine materials due to their outstanding mechanical properties that are maintained even at high temperatures. Table 6 summarises the machinability of the alloys that are commonly employed in metal AM processes.

Machinability of materials is related to tool wear modes and chip formation characteristics during cutting and also affects the surface and microstructural characteristics of the machined samples.

A research on turning DLD Ti6Al4V parts was conducted by Oyelola et al. [192] to study their machining behaviour and resulting microstructural and surface integrity changes. It was noted that microstructural inhomogeneity of deposited material had a negative impact on surface integrity and machinability of the manufactured part. Furthermore, it was stated that the control system used for the machining operations should be able to adapt to varying cutting forces and conditions in order to obtain the best machining performance. This requirement can be explained with microstructural inhomogeneity of

Table 6 Metallic materials and alloys that are commonly employed in AM applications

Material	Definition	Machinability	Application examples
Stainless steel	Chromium content higher than 11% [188]	Lower machinability than common steels	Energy industry (fossil fuel energy plants), biomedical industry (implants) automotive industry (exhaust systems)
Nickel-based superalloys	Higher than 50% nickel content [189]	Difficult to machine as they maintain good mechanical properties at high temperatures [188, 189]. These alloys have a great affinity to common cutting tools' materials that leads to high tool wear rates [190].	Aircraft turbine components that are exposed to high temperatures
Cobalt-based superalloys	Cobalt-based alloys have similar properties, i.e. high hardness and wear resistance, and low thermal conductivity [191].	Difficult to machine as they maintain good properties at high temperatures [188, 189]. Cobalt-based alloys also lead to high tool wear rates.	Aerospace industry (turbine and rocket motors), submarine and chemical industries (nuclear reactors, heat exchangers and gas turbines)
Titanium alloys	Excellent combination of wear resistance and hardness and good corrosion behaviour [188]	During machining, these alloys tend to generate crater wear on cutting tools.	Biomedical industry (hip implants)
Aluminium alloys	They were the first type of alloys employed in high performance machining applications due to their high machinability.	Malleable alloys lead to the generation of BUE (built-up-edge) wear mode in the cutting tools. Cast alloys lead to cutting tool abrasion due to the presence of silicon in the alloys that is a highly abrasive element.	Automotive industry (wheels), industrial machinery and tool industry, thermal and electric installations

AM parts and would be especially valid for FGM. In another study, Hojati et al. [193] investigated the machinability of AM Ti-based alloys and it was compared with that of a standard material in terms of cutting forces, specific cutting energy, surface quality and chip formation mechanism. The results showed that there were no significant differences in regards to the cutting forces. However, the machining of AM samples led to the formation of continuous wavy-type chips that were larger than those of the standard samples. Aldwell et al. [194] compared the machining of bulk and AM Al6061 samples, i.e. the cutting forces, the chip formation mechanism and the resulting surface morphology. It was concluded that a good machinability of AM samples could be achieved when there was a strong bonding between the layers and also when the part porosity was low. Therefore, the optimisation of process parameters for producing AM parts with higher homogeneity and minimum porosity is critical in order to improve their machinability.

Guo et al. [16] analysed the effect of the building direction during the DLD process on mechanical properties, microstructure and machinability of AISI 316L samples. Two building directions were investigated, and then the produced samples were machined by dry milling to meet the requirements for surface integrity and dimensional accuracy. It was found that the homogeneity and microstructure of the produced AM parts were dependent on the build direction and as a consequence the cutting forces, the tool wear and the resulting surface roughness deferred, too. It was concluded that some anisotropic characteristics of AM parts could be beneficial for the follow-up machining operations. Calleja et al. [195] studied the machinability of Inconel 718 samples produced with a hybrid AM process that combined DLD with machining. Cutting forces and specific cutting energy during turning and milling operations together with the resulting roughness and microhardness of the heat-treated DLD samples were compared with the results obtained for standard Inconel 718 samples. It was found that the cutting forces and microhardness were higher for the AM samples while the best surface roughness was obtained for the standard samples.

In summary, it can be stated that the machinability of AM parts is not sufficiently investigated and also taking into account the constantly growing number of AM materials, further research is required. In addition, the laser-material interactions when processing metallic powders should be studied further to understand better the underlying conditions that lead to the formation of hardened phases and non-uniform microstructures and thus are detrimental to the machinability of AM components.

6.2 Part deformations

The control of dimensional and geometrical accuracy of AM parts in time is another challenging issue in broadening the use of hybrid AM solutions. Residual stresses generated during the AM process can lead to part deformations and distortions. Therefore, post-processing operations have to be properly planned considering the actual geometry and dimensions of the AM parts and thus ensuring the required accuracy with respect to their design. As a result, part inspections are very important in planning post-processing operations and thus determining the actual deviations of AM part geometries from their intended designs.

The uncertainty of additively manufactured part dimensions is one of the greatest concerns when combining both additive and machining processes. During the machining processes, tool may find excess of material in non-expected places, which can cause tool damage or inadequate cutting [196]. Therefore, a great effort has been made to understand and control part deformations during AM. Paul et al. [197] proposed a model for calculating the deformation of workpiece during AM processes that are due to thermal stresses. It was found that the overlap between successive scanning paths, also referred to as hatch spacing, leads to continuous melting and re-solidification cycles that, in turn, determines the accumulated thermal stresses. Consequently, the developed stresses entail part distortions and dimensional inaccuracies. In addition to the hatch spacing, Das et al. [198] also studied the effects of layer thickness, support structures and build orientations on geometrical and dimensional accuracies of LPBF parts. It was found that the building direction was a crucial parameter as it affected the properties and dimensional accuracy of parts and determined the amount of support structures needed. An approach was proposed to define the optimal part orientation and thus minimising the support structures. However, the approach still required empirical data for validation purposes. In addition, the model did not consider some important factors in determining the optimal part orientations such as the resulting thermal stresses. Eisenbarth et al. [199] investigated the distortion of parts manufactured using two different hybrid AM approaches: (1) continuous DLD build-up of material with subsequent milling and (2) interrupted DLD build-up alternated with milling. It was shown that each consequent DLD step led to a higher bending of the developed part, whereas the milling steps reduce it to a certain degree. Also, it was noted that, an inspection operation was required between the deposition and machining stems due to the part distortions.

However, the inspection of certain regions, such as internal cavities or complex overhanging features is also a challenging task. A summary of different methods used for inspecting AM parts with their open issues and challenges is provided in Table 7 [200].

Laser-based inspection methods for AM parts were investigated, too. Montinaro et al. [201] used a flying laser scanning thermography for inspection of AM parts with high signal to noise ratio of the measurements. However, it was noted that

Table 7 Inspection methods for AM parts with their open issues and challenges

Inspection method	Open issues and challenges
Visual inspection	Limited to surface defect detection
	Internal and difficult-to-access regions cannot be examined.
Liquid penetration test	Incompatible with porous materials
	Only provides information about surface discontinuities.
Magnetic particle testing	Exclusive for ferromagnetic materials
	No information about the bulk or internal features
Eddy current testing	Exclusive to electrically conductive materials
	Also detects unwanted signals.
	Sophisticated algorithms for signal processing are required.
Ultrasonic testing	Inspection once the part is finished which may lead to rejection at the end of manufacturing process [201].
X-ray	Again, inspection of only finished parts which may lead to rejections at the end of the manufacturing process [201].

due to the higher surface roughness of metal AM parts laser-based inspection methods might not be a suitable solution.

In addition, the integration of inspection operations into hybrid AM solutions should also be considered. Their maintenance and protection from fumes and cutting fluids together with the integration of inspection software with CAD/CAM software also present challenges and open issues in developing hybrid AM systems and thus increasing their efficiency and throughput.

6.3 Process related challenges

Hybrid AM solutions have open issues and challenges associated with each integrated technology and also due to the execution of all operations in the same manufacturing system. The main process-related issues in hybrid AM can be clustered into (1) process parameter optimisation, (2) cleanness, (3) material oxidation and (4) issues related to the AM processes.

The process optimisation is one of the shortcomings of metal AM technologies and also in hybrid AM systems. There is no sufficient knowledge how post-processing parameters might affect AM parts [81]. Considering the case when machining operations are used for post-processing AM parts, in spite of the fact that it is a mature technology, there is not sufficient research on their effects on the resulting surface integrity. Additionally, a key open issue in broadening the use of hybrid AM solutions is the achievable repeatability and thus whether they can meet the requirements for serial production. Especially, it is necessary to determine geometric and dimensional tolerances that can be achieved consistently together with respective mechanical and microstructure properties of the hybrid parts. A systematic analysis of various factors affecting the processing conditions of integrated processes is required. This will allow processing parameters and

equipment accuracy and repeatability to be controlled sufficiently well to meet standardised requirements that are also yet to be developed.

Coolant management and cleanness, especially for the laser-based AM technologies, are other critical issues when integrating AM processes with conventional machining in hybrid AM systems [81, 196]. The issues associated with cleanness were studied by Boivie et al. [123] and it was found that all chips and cutting fluids should be carefully removed before starting any AM process. Otherwise, it could deteriorate the machinability of difficult-to-cut materials such as Ti-based alloys or Ni-based alloys. As for the cutting fluid, it can be mixed with the powder particles and affect their absorptivity and, consequently, the bonding with the substrate material [196]. Additionally, machine guiding systems must be protected and properly sealed in order to avoid powder particles to abrade the moving components.

Another important issue in hybrid AM systems is the lack of a closed chamber to avoid powder oxidation during the AM processes. As was already mentioned, several hybrid AM systems utilised inert gases to shield processing areas and thus minimising the oxidation during laser-material interactions. However, depending on process parameters and reactivity of employed materials, this may not be sufficient to avoid any oxidation. In turn, the oxidation can induce defects in the manufactured parts. Hebert et al. [202] found that when the AM process utilised reactive materials such as titanium-based alloys, oxide layers might be formed in spite of shielding conditions except when using extremely high vacuum. In addition, the formation of hydroxides and hydrated oxides should also be addressed. While oxides tend to strengthen the materials, hydroxides can act as lubricants and deteriorate the strength of AM parts.

As it was already discussed, LPBF and DLD are the most commonly employed laser-based AM technologies and, in

Fig. 28 Example of FGM: deposition of copper on a steel substrate [184]

Steel substrate   Copper wall   10 mm
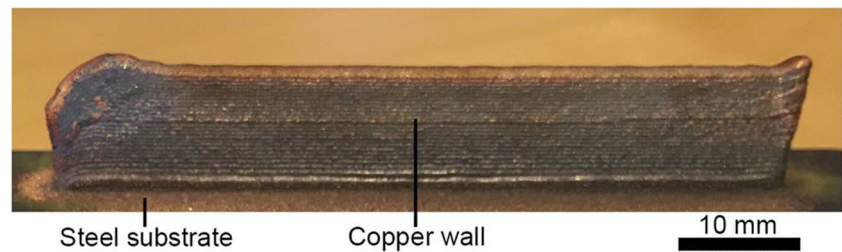
turn, they are the most commonly employed in hybrid AM systems, too. LPBF enables the creation of complex parts with high accuracy, but it is a relatively slow process. In addition, support structures have to be removed in follow-up post-processing operations. Depending on the geometry and the location of those support structures, their removal can represent a challenge if they are difficult to reach with the cutting tools. Additionally, LPBF can be integrated only into 3-axis vertical machine tool configurations. Therefore, the LPBF capabilities for producing complex part geometries may be reduced due to the constraints imposed by post-processing operations. Furthermore, powder management is another important issue to consider in integrating the LPBF process in hybrid AM systems.

At the same time, the DLD technology is faster than the LPBF one and therefore any hybrid AM system that integrates a DLD head will have a higher throughput. Also, the DLD allows complex parts to be built without the need for support structures because of the higher positioning flexibility of the hybrid machine tool configurations. Nevertheless, the DLD head inclination and position have to be carefully controlled to maintain the optimum deposition rates and parts accuracies. However, there are some shortcomings, too, as the overall quality of DLD manufactured parts, i.e. their dimensional and geometrical accuracy and surface integrity, is worse than that of LPBF parts. Additionally, special care should be taken to avoid any collisions between the workpieces, the DLD head and the cutting tools during both deposition and post-processing operations.

6.4 Work holding–related challenges

Machining of AM parts directly can be challenging because of their lightweight and complex shapes. These both characteristics can lead to problems with work holding and vibration, and thus can result in poor process yields. Work holding systems have to be designed and implemented in such a way that they should ensure reliable workpiece fixation and the required accuracy and repeatability during machining operations. Thus, these systems should be designed to withstand the cutting forces during machining operations without any displacements while providing sufficient access to all surfaces that require some post-processing. However, in the case of hybrid AM solutions, the geometries of the AM structures are complex and can incorporate internal cavities with different stiffness and properties. Therefore, the work holding systems have to be sufficiently flexible while providing adequate support for processing parts with varying geometries and rigidity. This is not an easy design and implementation task.

One of the solutions that have been proposed for holding the workpiece during the machining operations is depicted in Fig. 29. First, the workpiece has to be embedded into an auxiliary plastic support structure that is afterwards removed [203]. The configuration of the auxiliary support system should ensure both the required workpiece fixation during the machining operations and also access to the surfaces that should undergo some post-processing, e.g. the flat surfaces at both ends of the rectangular pipe in Fig. 29.

Fig. 29 A special clamping solution designed by Renishaw for holding AM workpieces during the machining operations. **a** The AM workpiece. **b** The work holding system [203]
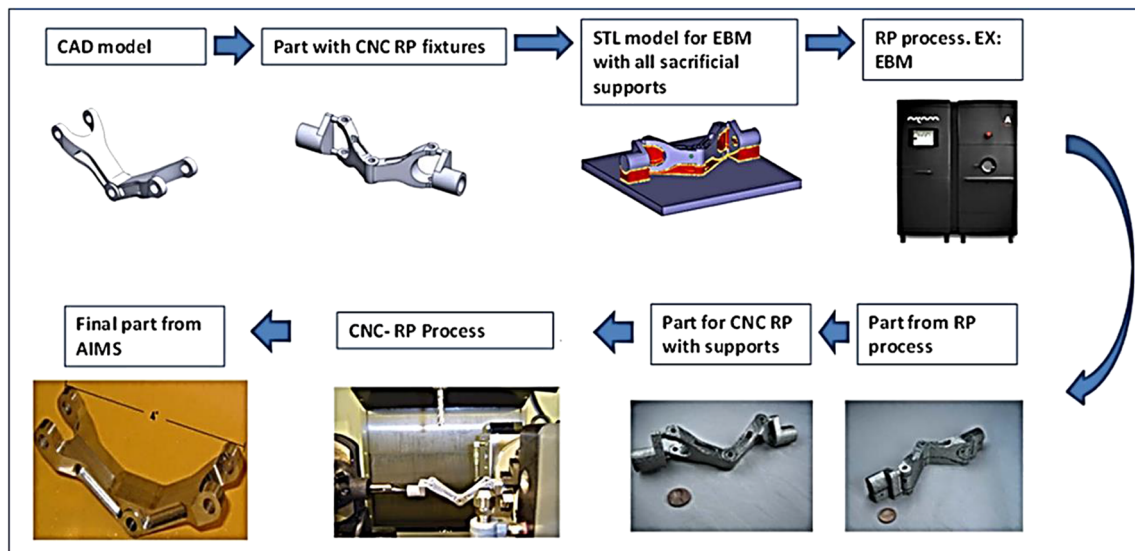

(a)   (b)
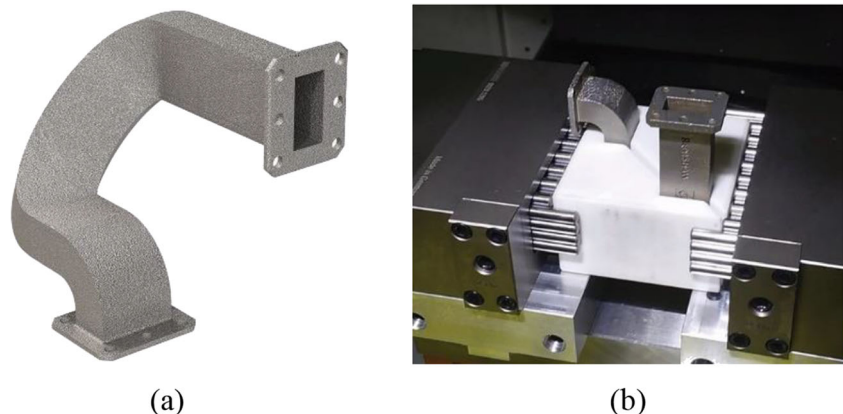
Fig. 30 Sacrificial features for part positioning [10]. The figures are reused under the Creative Commons CC-BY licence

Manogharan et al. [10] proposed another solution for clamping and positioning of AM workpiece that uses some sacrificial supports. Especially, the sacrificial support has to be built together with the workpiece during the AM process and thus ensure the required positioning and fixation during the machining operations. Figure 30 shows the workflow suggested in designing and implementing such work holding systems. As it can be seen, the CAD model of the part have to be modified to add required sacrificial features while at the end a further post-processing step is required to remove them.

One of the main advantages of using single setup hybrid additive manufacturing systems is that they enable to reduce the time to define part zeros. This is an advantage not only in terms of productivity of the process, but also because it minimises the positioning-error that occurs when using multi-setup solutions [196]. In those cases that employ intermediate or special fixturing systems as the ones presented above, the design of rigid and appropriate fixturing systems will be of great importance to reduce those positioning problems.

7 Conclusions

The paper presents the research work on hybrid AM solutions that combine the capabilities of AM with post-processing technologies. The review has a special focus on powder-based AM processes that employ lasers as a heat source for material processing. Different hybrid AM solutions were reported and their capabilities and limitations were analysed. Additionally, an overview of commercially available hybrid AM systems is presented, too, that outline the machine specifications together with their advantages and limitations.

Furthermore, current and potential applications of hybrid AM are discussed. Finally, the open issues and main challenges associated with the hybrid AM solutions are discussed to suggest directions for future research. Especially, the open issues associated with machinability of common AM materials, part deformations, shortcomings of integrated processes and specially designed work holding systems are discussed.

The broader take up of metal AM technologies requires their seamless integration with post-processing technologies and thus addressing deficiencies of AM parts, i.e. their accuracy and surface integrity, and thus meeting the requirements of aerospace, automotive and biomedical industrial sectors. Hybrid AM solutions that integrate machining, heat and surface treatment operations have shown a clear potential to improve the surface finish, geometrical accuracy, mechanical properties and microstructures of metal AM components. The machining operations allow the required surface integrity and dimensional accuracy to be achieved while heat and surface treatments can be used to reduce porosity and improve the microstructure and mechanical properties of AM parts. Additionally, deformations and distortions of AM parts due to residual stresses along with other defects should be considered when planning the follow-up post processing operations. Therefore, the integration of part inspection solutions into the hybrid AM systems is crucial in order to produce parts that meet the industrial requirements.

Recently, hybrid AM solutions have attracted the interest of machine tool manufacturers and also of end-user companies and a significant number of hybrid machine tools have been developed in the last decade and are now commercially available. In addition, modular hybrid solutions have been developed, too, that can be integrated into existing machining or AM systems. It is evident that hybrid AM systems are very important in broadening the industrial application of metal

AM technologies, especially in high-tech industries such as biomedical (dental applications and protheses), aerospace (turbine blisks, cases, etc.) or automotive (engine cylinders). Another key application of hybrid AM systems is the repair of high-value components and the manufacture of FGM parts with tailored mechanical properties.

In spite of all the benefits and the potential of hybrid AM systems shown so far, several open issues and challenges remain that have to be addressed, in particular:

- There is still not sufficient research on machinability of AM parts and optimisation of both AM and post processing technologies with a special focus on difficult-to-machine materials.
- The laser-material interactions when processing metallic powders should be studied further to understand better the underlying conditions that lead to the formation of hardened phases and non-uniform microstructures and thus are detrimental to the machinability of AM components.
- Issues related to AM processes, such as part distortion, varying and not constant mechanical properties and microstructure of produced AM parts, have to be considered and controlled when planning and implementing hybrid AM solutions.
- Powder oxidation in out-of-chamber AM processing, relatively low productivity, the necessity for removing any support structures and possible collisions are some other open issues preventing the broader use of the hybrid AM systems that have to be addressed.

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Hany Hassanin: Writing review

Faris Tarlochan: Writing review

Stefan Dimov: Analysis and writing review

- Khamis Essa: Conceptualization, Analysis and Writing review.

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Declarations

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