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Hybrid metal additive manufacturing: A state–of–the-art review

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A R T I C L E I N F O

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A B S T R A C T

This paper starts from the early developments and working principles of the additive manufacturing of polymers, continues with a glimpse on the extension to metals with identification and characterization of the two most widespread technologies, and ends with an overview of the recent developments in hybrid metal additive manufacturing.

Earlier classifications of hybrid manufacturing with roots on the utilization of primarily processed raw materials in the form of ingots, sheets, rods, tubes, profiles, powders and pellets are revisited in the light of the emergence of a new type of hybridization resulting from the combination of additive manufacturing with traditional manufacturing processes.

Special emphasis is given to the combination of additive manufacturing with forming processes with the two-fold objective of (i) increasing the applicability domain of metal additive manufacturing and overcoming its limitations related to low productivity, metallurgical defects, rough surface quality and lack of dimensional precision, and (ii) adding flexibility and fostering new applications of traditional forming processes.

1. Introduction

Hybrid manufacturing (HM) is a designation used for manufacturing processes that combine different technologies as a mean to overcome their individual limitations and benefit from their intrinsic advantages (Chu, 2014). The roots of HM are found in subtractive manufacturing (SM) but the concept and applications evolved with time to incorporate other traditional manufacturing technologies, such as welding, assembly and forming (Zhu et al., 2013; Lauwers et al., 2014).

This paper is focused on the emergence of a new type of hybridization with roots on metal additive manufacturing (MAM), which is a technology that enables building-up parts with complex geometries by adding feedstock metal layer-upon-layer. The goal is to increase the applicability domain of MAM by overcoming its limitations related to low productivity, metallurgical defects, rough surface quality and lack of dimensional precision through combination with other manufacturing technologies. Conversely, hybridization based on MAM can also be seen as a way of adding flexibility and reducing the amount of material wastage in traditional manufacturing processes (Lorenz, 2015).

The initial developments of metal hybrid additive manufacturing were based on the utilization of multiple thermal energy sources and combination of MAM with metal cutting to improve productivity and quality of the built parts. These developments led to the commercialization of the first hybrid metal additive manufacturing systems in the mid 2010's.

The combination of MAM with metal forming is more recent and was initially aimed to improve the shape of the deposited material layers by local plastic deformation, while providing higher stiffness and wear resistance to the built parts. However, hybridization based on the combination of MAM with forming has been evolving and expanding quite rapidly in recent years by encompassing new concepts taken from sheet and bulk metal forming processes.

Under these circumstances, the objective of this paper is to present a state-of-the-art review focused on this new emerging type of hybridization with roots on MAM. Its contents may be seen as an extension of previous reviews in the field of HM such as those published by Zhu et al. (2013) and Lauwers et al. (2014), which were mainly focused on HM with roots on primarily processed raw materials and linked to subtractive manufacturing and other traditional manufacturing technologies.

The paper is structured in three main parts besides this introduction. The first part provides an overview of the different additive manufacturing processes and discusses its working principles and main

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characteristics with emphasis on those applicable to metals. The second part revisits earlier classifications of hybrid manufacturing (HM) in the light of new developments based in metal hybrid additive manufacturing. The third part presents an overview of the main research publications in metal hybrid additive manufacturing with special focus on the combination of MAM with metal forming, which to the authors knowledge, has only been partially covered in a paper by Merklein et al. (2016).

2. Metal additive manufacturing

2.1. Development timeline in a glimpse

The first developments in additive manufacturing were made in the early 1980's by Hideo Kodama, who worked on the utilization of ultraviolet lights to harden polymers and create solid objects (Kodama, 1981). However, additive manufacturing is considered to have emerged as a technology in the late 1980's with the development of stereolithography (SLA) by Charles Hull (1990) and fused deposition material (FDM) by Scott Crump (1991). Both processes were used to fabricate three-dimensional parts by layering polymers in thin horizontal cross-sections with the aid of a localized thermal energy source; ultraviolet light in SLA and the hot end of a nozzle in FDM.

The commercialization and use of the first equipment in the early 1990's allowed in-house fabrication of polymer prototypes with significantly reduced lead time and explains the reason why additive manufacturing was initially referred to as 'rapid prototyping'. Since then, innovations in equipment and material made possible to significantly expand the applicability domain of additive manufacturing from prototypes into costumer-oriented parts for machinery, electronics, aerospace, automotive and medicine, among others, using a wide spectrum of materials that include polymers, ceramics, composites and metals.

The use of additive manufacturing in metals, which are the most commonly used engineering materials, only started in the early 1990's with the development of binder jetting by Ely Sachs and co-workers (Sachs et al., 1993). The utilization of inkjet style printer heads in binder jetting to spray successive layers of metal powders with adhesives and stick them together into three-dimensional parts, explains the origin of the term 'three-dimensional printing' (or, simply '3D printing') as a synonym for 'additive manufacturing'.

The development of lasers capable of delivering the high amounts of energy that are needed for processing metal powders in sintered or fused states in the mid 1990's paved the way to the development of a process known as direct metal laser sintering (DMLS) (Shellabear and Nyrhilä, 2004), and to the commercialization of the first equipment for metal additive manufacturing (MAM). DMLS was an extension to metals of selective laser sintering (SLS) that started to be developed in the late 1980's by Carl Deckard (1989) for the additive manufacturing of polymers (Ning et al., 2005).

In the late 1990's, Arcam from Sweden introduced an electron beam thermal energy source for metal additive manufacturing (Larson, 1998).

In parallel with the development of lasers, Dickens et al. (1992) presented a process named as '3D welding' capable of producing near net shape metal parts by retrofitting and combining conventional welding machines with robots. The process opened the way to the combination of electric arc and computed added manufacturing (CAM) software to control the tool paths and the start and stop points of the welder and wire feeder that are needed to convert a model into a three-dimensional metal part. Although Dickens et al. (1992) and Prinz and Weiss (1993) are considered to be the first developers of wire-arc additive manufacture (WAAM), the working principle of using an electric arc as the thermal energy source and welding wire as feedstock to manufacture large components had already been successfully applied previously.

Since these pioneering breakthroughs, there has been significant new developments and applications in the field of MAM. In what follows, authors present a classification of the different additive manufacturing processes, explain their working principles and discuss its main characteristics, with emphasis on those applicable to metals.

2.2. Classification

The EN ISO/ASTM 52921 (2015) standard classifies additive manufacturing processes into seven different categories (Fig. 1). Four of these categories are nowadays utilized to build metal parts; binder jetting (BJ), powder bed fusion (PBF), sheet lamination (SL) and direct energy deposition (DED). The other three categories; vat photopolymerization (VP), material jetting (MJ) and material extrusion (ME) are mainly used as indirect additive manufacturing when concerns its application to metals.

The difference between direct and indirect metal additive manufacturing (MAM) processes is related to the use given to the built parts. In direct MAM, the metal built parts are the final products and are straightforwardly fabricated in accordance with the design specifications and requirements. In indirect MAM, the built parts consist of master patterns or tools that are subsequently used by traditional manufacturing processes to obtain the final metal parts (Montero et al., 2020).

As a result of this, indirect MAM cannot be uncoupled from traditional manufacturing processes, such as investment casting, sand casting (Mitra et al., 2019), die casting and injection molding (León-Cabezas et al., 2017), and is largely focused on 3D printing of non-metallic materials such as polymers, photopolymers, ceramics, waxes, resins and composites.

2.2.1. Direct MAM

Direct MAM consists of the four categories that are nowadays utilized to build metal parts (Fig. 1); binder jetting (BJ), powder bed fusion (PBF), sheet lamination (SL) and direct energy deposition (DED).

Binder jetting consists of spraying a stationary loose bed of powder placed on a build platform with a liquid adhesive through an inkjet style printer in order to stick the powders together into a cross-section, layer-upon-layer (Sachs et al., 1993) (Fig. 2a). The built platform is lowered after the creation of each layer to allow the next layer to be formed and the process continues until obtaining a 'green part' with low strength and approximately 60% relative density. The green part is then heated in a controlled atmosphere to remove the adhesive and to sinter (bond) the individual particles into a 'fully dense' metal part.

The increase in density during sintering is obtained via shrinking and loss of dimensional precision, which are considered to be the main drawbacks of binder jetting (Ziaee and Crane, 2019).

Sheet lamination consists of joining thin metal sheets layer-upon-layer (via a system of feed rollers), to build a single piece that is subsequently cut out by milling into the required part (Fig. 2b). Adhesive bonding, ultrasonic welding and friction stir welding can be used to join the successive sheets on top of one another (Derazkola et al., 2020).

Friction stir welding starts nowadays being also associated to an emergent category of direct MAM, named 'friction-based additive manufacturing', which is based in multi-layer construction with metal feedstock other than sheets (Fig. 2c). This category is not listed in Fig. 1, (adapted from the EN ISO/ASTM 52921 (2015) standard), and includes additive friction stir (AFS), and friction surfacing (FS).

AFS uses a non-consumable tubular tool to generate heat and performs the consolidation by plastic deformation of the metal powder that flows through the tube and is deposited onto the base plate. FS was initially developed as a surface coating process (Palanivel and Mishra, 2017) and uses a metal consumable rod that is rotated and pressed against the substrate to generate successive boundary layers for building the parts.

Powder bed fusion fabricates metal parts by slicing its geometry into layers and adding the individual particles of powder together one layer at a time on a build platform by means of a focused thermal energy source (Fig. 2d) (Bhavar et al., 2014). The processing route is similar to that of BJ because the powder remains static inside the build platform and is selectively bonded layer-upon-layer according to a predefined

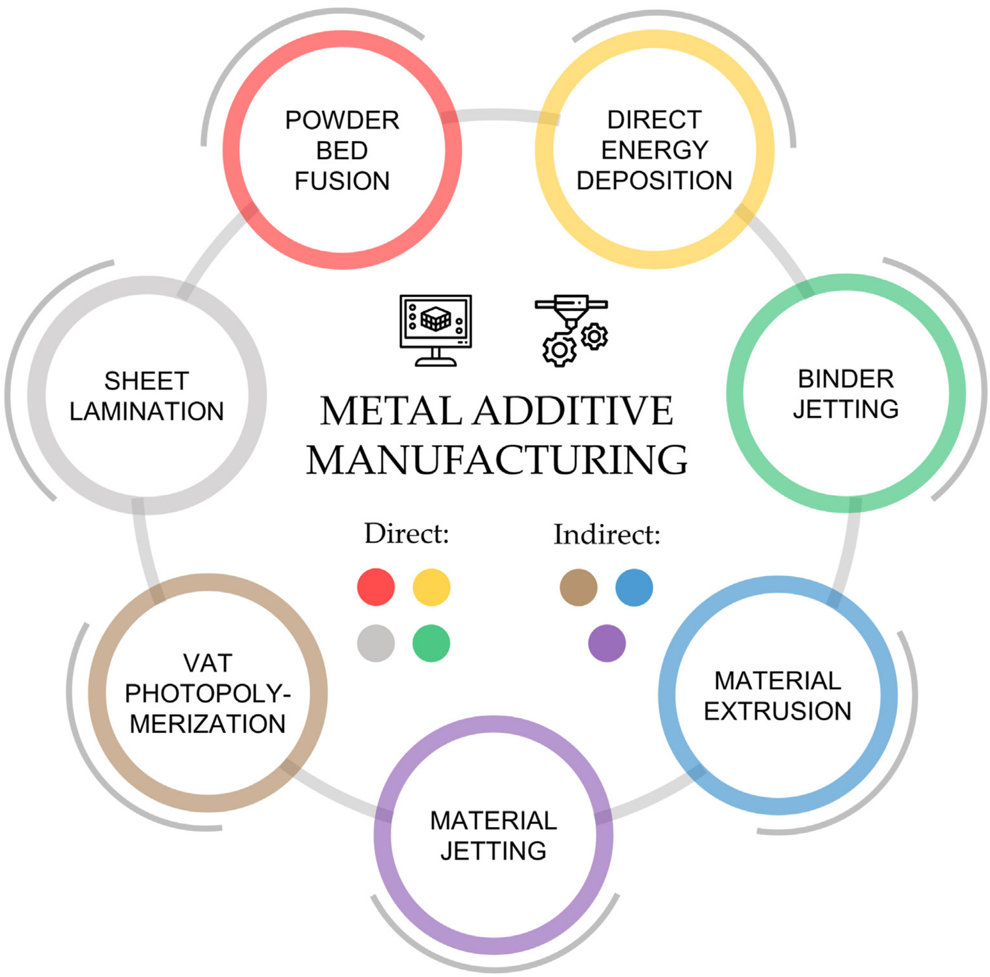

Fig. 1. Classification of additive manufacturing with identification of its direct and indirect suitability to build metal parts (adapted from the EN ISO/ASTM 52921 (2015) standard).

two-dimensional path until obtaining the required part shape and height. However, in contrast to BJ that uses a liquid binder, PBF employs a thermal energy source for joining by fusion the individual particles of powder together.

Direct energy deposition fabricates metal parts by feeding powder or wire through a nozzle onto the build part where it is melted by means of a focused thermal energy source (Fig. 2e) (Saboori et al., 2017). The process circumvents the use of binders and differs from PBF because the feedstock flows through a feeding device and melts at the exact time of deposition, instead of remaining static inside the build platform during construction of the part, layer-upon-layer.

In contrast to binder jetting (BJ) and sheet lamination (SL), which have a limited number of commercial applications (DebRoy at el., 2018), both powder bed fusion (PBF) and direct energy deposition (DED) have a broad applicability in the construction of three-dimensional metal parts. The end of this section will provide additional information on powder bed fusion and direct energy deposition processes because of their key role in MAM.

2.2.2. Indirect MAM

Indirect MAM consists of three categories that are mainly used to build polymer and highly-filled polymer parts made from mixtures of metals and/or ceramic powders with polymers (Fig. 1); vat photopolymerization (VP), material jetting (MJ) and material extrusion (ME). The applicability of these processes to the fabrication of pure or alloyed metal parts is scarce.

Vat photopolymerization creates three-dimensional parts by selectively curing and bonding together (by cross-linking) special liquid resins (called photopolymers) through light-activated polymerization (ultraviolet light). This category includes laser-based processes such as stereolithography (SLA) and direct light processing (DLP) that are performed by building up single photopolymer layers (SLA) or full two-dimensional patterns (DLP) while integrating a recoating mechanism (Appuhamillage et al., 2019). A variant known as two-photon lithography can be utilized for high-precision construction, in which ultraviolet-induced polymerization occurs solely in the area of interference between the two laser beams (Oran et al., 2018).

The major drawbacks of photopolymers is their cost, which is higher than that of thermoplastics, and their lack of structural strength leading to degradation and deformation of parts over time.

Material jetting create parts by depositing droplets of liquid photopolymer resin layer-upon-layer (via inkjet style printer heads) that are cured and bonded together by exposure to ultraviolet light (Yap et al., 2017). The process uses the same type of printer head technology of binder jetting but while binder jetting deposits liquid adhesive onto a stationary loose bed of powder placed on a build platform in order to solidify the cross section of the part, layer-upon-layer, material jetting deposits the build-materials directly on the part under construction.

Additive manufacturing processes based on material jetting are among the most precise and capable of producing smooth surfaces with fine details and high accuracy. However, its utilization is limited by the cost of the photopolymers, by its limitations in strength and by restrictions on the size of the parts due to its long processing run times. The latter may be circumvented by the use of two or more print heads. This is

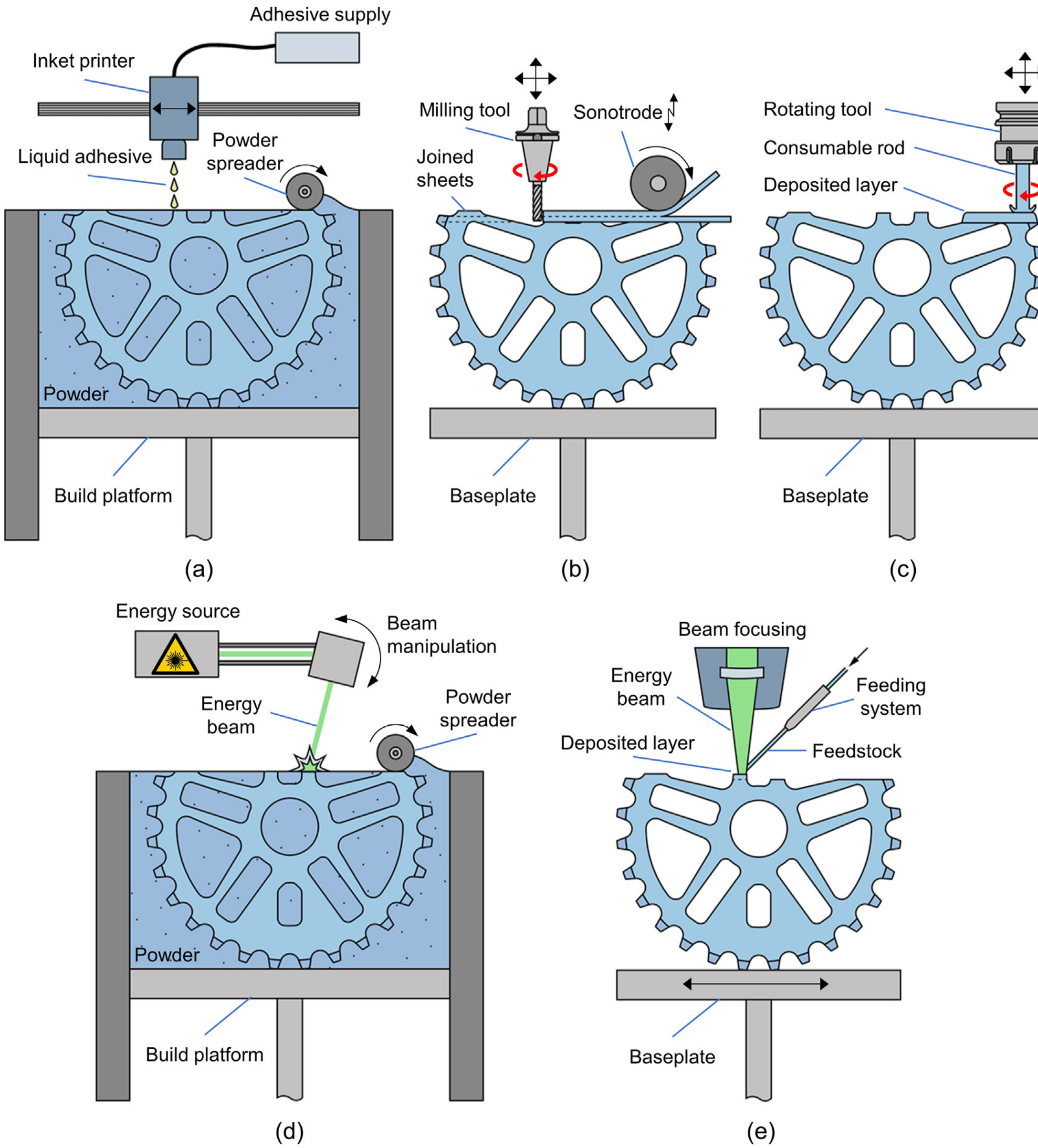

Fig. 2. Schematic representation of the working principle of several additive manufacturing categories with main terminology.

(a) Binder jetting (BJ);
(b) Sheet lamination (SL);
(c) Friction surfacing (FS);
(d) Powder bed fusion (PBF);
(e) Direct energy deposition (DED).

the case, for example, of a process known as 'drop-on-demand' (DOD) used to produce the polymer patterns of investment casting, which uses two print heads; one for depositing the build material and the other to deposit a dissolvable support structure that facilitates the overall design of the three-dimensional printing path (Li et al., 2014).

Material extrusion deposits a thermoplastic polymer layer-upon-layer to build a three-dimensional part by pushing the polymer through a heated nozzle in a continuous stream (Gonzalez-Gutierrez et al., 2018). In fused filament fabrication (FFF), material extrusion is performed with filaments that are pushed by driving wheels into a liquefier and, afterwards, into the nozzle for subsequent deposition. This technique is very effective for processing a vast amount of thermoplastic materials, but only if the feedstock filaments can be properly spooled and are rigid enough to be pushed by the driving wheels. Fused deposition modeling (FDM) that was previously mentioned in Section 2.1 is another important process belonging to this category.

Material extrusion based processes are not as fast or accurate as other additive manufacturing processes. However, their utilization is relatively widespread for the cost-effective fabrication of non-functional prototypes due to the low cost of thermoplastic materials such as Nylon and ABS.

2.3. Powder bed fusion and direct energy deposition

Fig. 3 presents a classification of the main MAM processes belonging to the aforementioned categories of powder bed fusion (PBF) and direct energy deposition (DED). The classification distinguishes between the type of thermal energy source for heating the feedstock (laser beam, electron beam and electric arc) and the supplied feedstock format (powder and wire).

The MAM processes based on electric arc are group under an

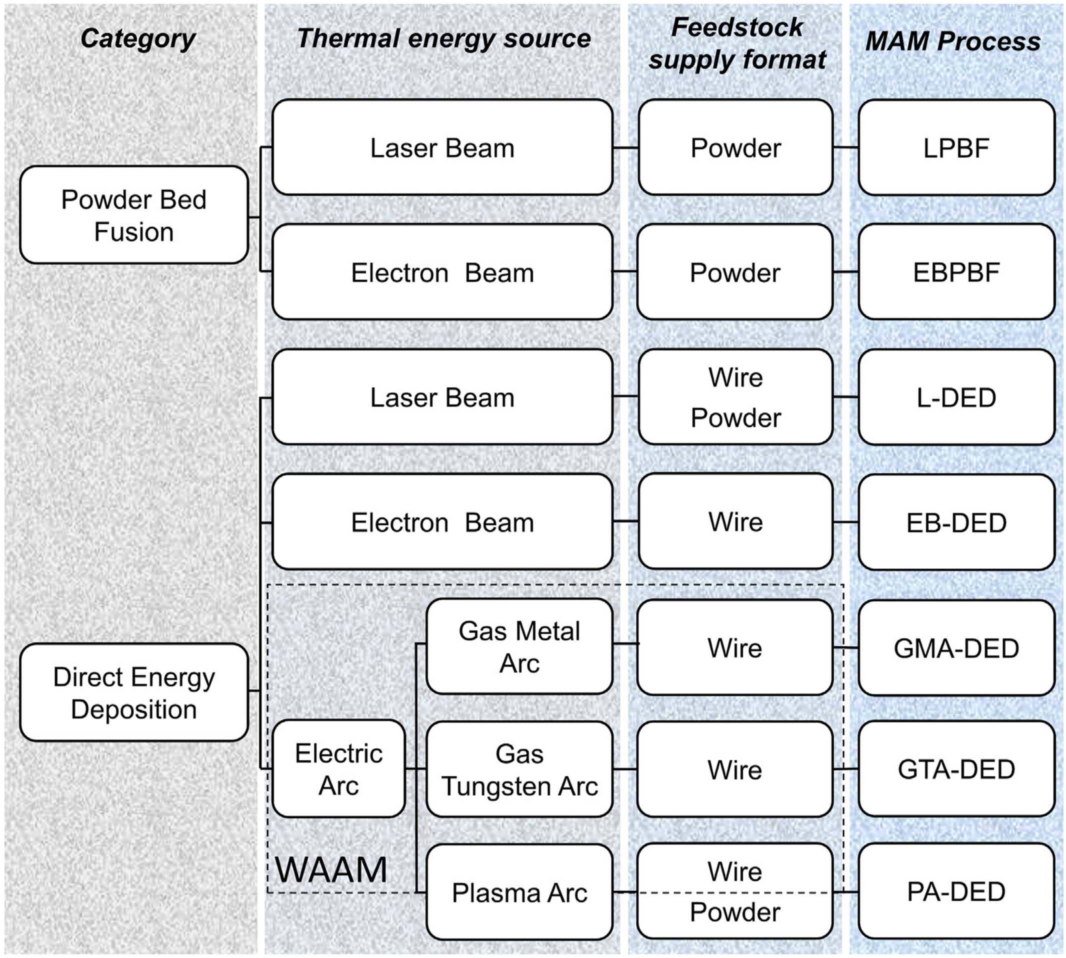

Fig. 3. Classification of the metal additive manufacturing (MAM) processes belonging to the two categories (PBF and DED) with widespread application in the construction of three-dimensional metal parts.

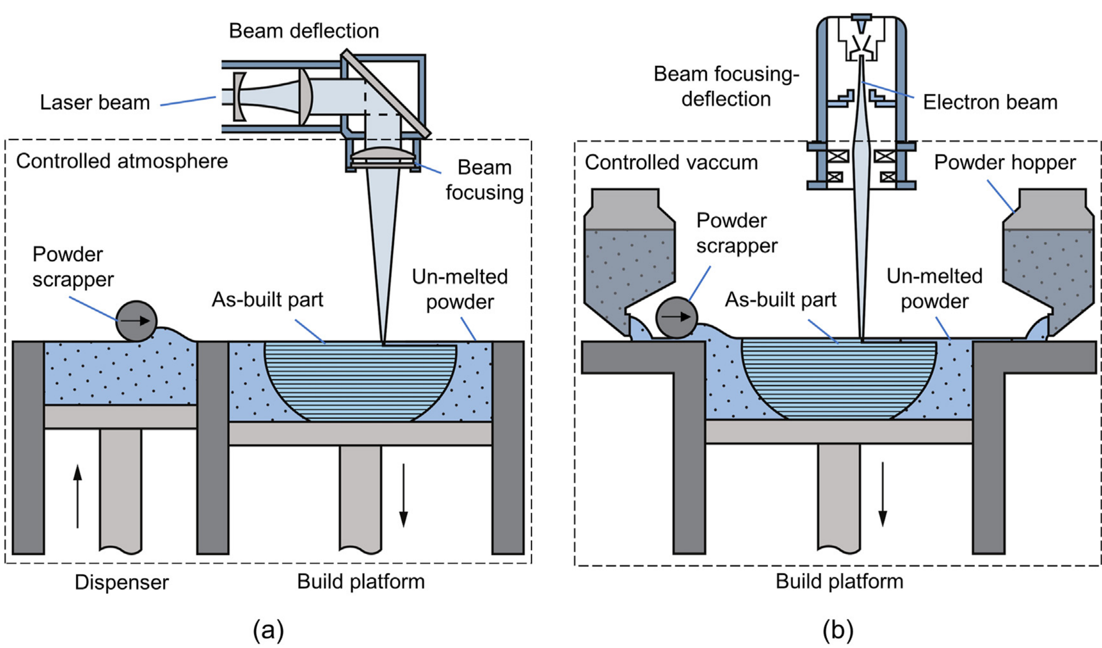

Fig. 4. Schematic representation of the working principle of the following PBF-based processes.

(a) Laser powder bed fusion (LPBF);
(b) Electron beam powder bed fusion (EBPBF).

individual subcategory extracted from DED designated as 'wire arc additive manufacturing' (WAAM).

2.3.1. PBF-based processes

The two PBF-based processes listed in Fig. 3; laser powder bed fusion (LPBF) and electron beam powder bed fusion (EBPBF) can be utilized to build complex prototypes and end-use metal parts with good resolution, reduced material wastage and efficient recycling of the un-melted powder. They are primarily differentiated by the source of thermal energy.

Laser powder bed fusion (LPBF), which is one of the oldest MAM processes, utilizes a laser beam thermal energy source to selectively melt and consolidate powder into solid shapes layer-upon-layer (Fig. 4a). Reflective mirrors are used to move the laser beam according to a predefined two-dimensional scanning path in controlled environment atmospheres of argon or nitrogen, depending on whether the metal is reactive or not (Pragana et al., 2020).

LPBF is a mature MAM process with a significant amount of literature focused on the final properties of the built parts made from an extensive range of metal alloys (Bhavar et al., 2014). The widespread use of this process combined with the continuous improvement of equipment by manufacturers allows, nowadays, obtaining deposition rates of up to 0.1 kg/h and surface roughness in the range of 10–20 μm. This explains the exponential growth of LPBF equipment sales in recent years (Wohlers, 2017).

The working principle of electron beam powder bed fusion (EBPBF) is similar to that of LPBF and the main difference is the source of thermal energy for melting the powder that in case of EBPBF is an electron beam instead of a laser beam (Fig. 4b). The change in the source of thermal energy is accompanied by several other modifications in the equipment because the electron beam is produced under controlled vacuum conditions and is focused and deflected by means of electromagnetic lenses, instead of mirrors. Pre-heating the feedstock to temperatures around 0.5 to 0.6 of its melting temperature is required to avoid powder spreading originated from electrostatic charging (the so-called 'powder pushed-away phenomenon') (Murr et al., 2012).

The utilization of EBPBF is not as widespread as LPBF in both research and industry. Still, EBPBF has paved its way towards certain industrial applications, especially when it comes to handle difficult-to-process materials such as cobalt and nickel alloys, titanium aluminides, niobium, or even cellular materials (Körner, 2016). The maximum deposition rates of EBPBF are slightly higher than those of LBBF and capable of reaching values up to 0.2 kg/h with surface roughness in the range of 15–30 μm.

2.3.2. DED-based processes

The main differences between the DED-based processes listed in Fig. 3

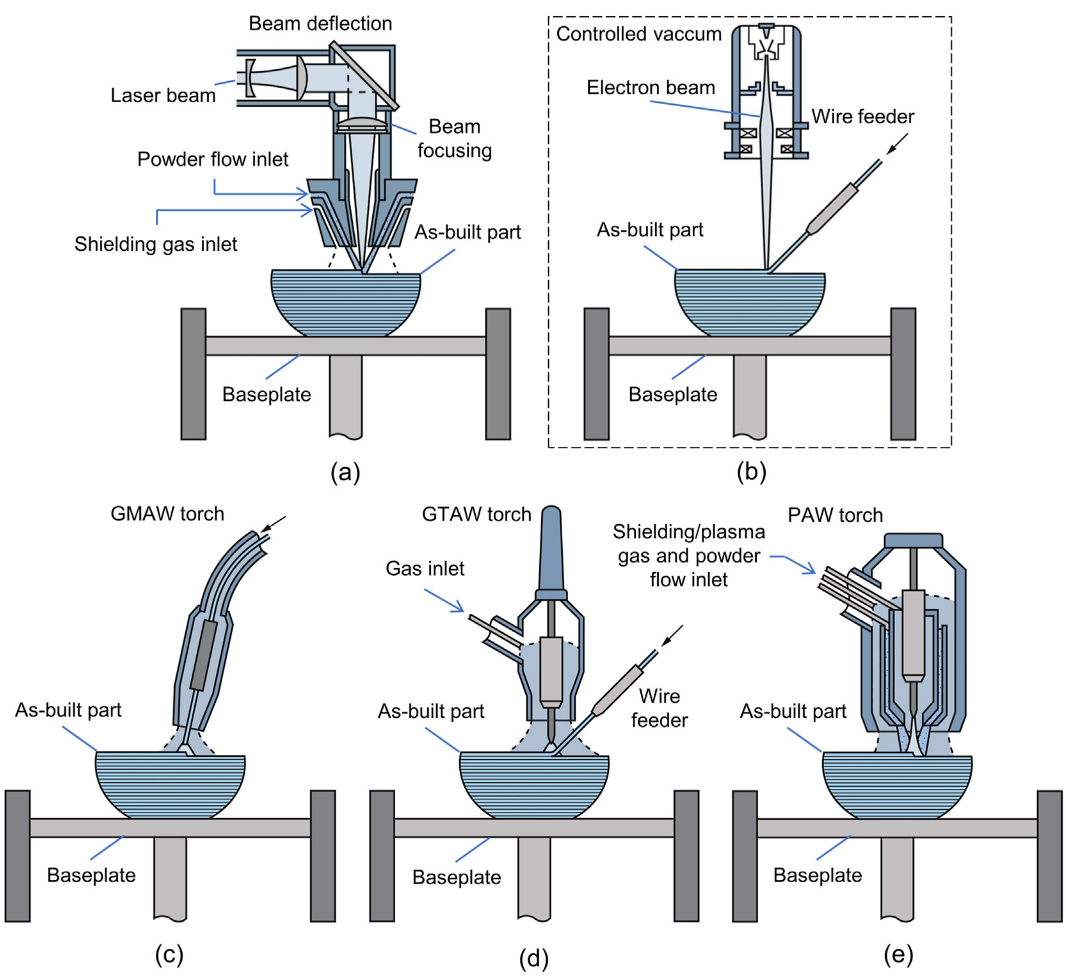

Fig. 5. Schematic representation of the working principle of the following DED-based processes.

(a) Laser direct energy deposition (LD-DED);
(b) Electron beam direct energy deposition (EB-DED);
(c) Gas metal arc direct energy deposition (GMA-DED);
(d) Gas tungsten arc direct energy deposition (GTA-DED);
(e) Plasma arc direct energy deposition (PA-DED).

originate from the sources of thermal energy and the systems used to deliver the feedstock and ensuring its simultaneous deposition and melting during construction of the parts.

Laser direct energy deposition (L-DED) utilizes the working principles of laser cladding to build three-dimensional metal parts, layer-upon-layer (Fig. 5a). The feedstock can be either powder or wire; in case of powder, material is segmented and fed through the laser head (usually coaxially), whereas in case of wire, material is fed by means of an independent system, separated from the laser head.

The maximum deposition rates using wire feedstock can reach values up to 2 kg/h, and surface roughness is typically above 30 μm. The process can be robotized to enhance path motion flexibility for the constructing of complex three-dimensional parts because it does not require the use of controlled environmental chambers. Shielding gases flowing from the laser head protect the melt pool from oxidation and act as carriers to assist powder transfer to the melt pool.

The working principle of electron beam direct energy deposition (EB-DED) is similar to that of L-DED apart from the substitution of the laser beam source of thermal energy by an electron beam operating under controlled vacuum conditions (Fuchs et al., 2018) (Fig. 5b). The process works exclusively with wire as feedstock due to poor handling of metal powder flow in vacuum, which could compromise the final quality and accuracy of the parts.

EB-DED enables fabricating large size parts with deposition rates ranging from 3 to 10 kg/h, depending upon the material and part features. The high deposition rates and large melt pools give rise to significant thermal stresses which require substrate and fixture considerations in some circumstances. The surface roughness of the built parts is irrelevant due to the necessity of performing secondary operations to obtain the final parts.

The processes grouped under the sub-category WAAM (wire arc additive manufacturing) in Fig. 3 refer to those using an electric arc as the source of thermal energy and having working principles similar to those of arc welding processes. WAAM-based processes are generally less accurate but faster than L-DED, due to deposition rates that may reach 5–6 kg/h. They are also more efficient than L-DED due to the larger energy requirements that are needed to turn electrical energy into a laser beam.

With regard to the comparison between WAAM and EB-DED, it may be said that deposition rate is higher, but accuracy is lower. However, the appeal of WAAM-based processes in research institutions and industry having their own welding equipment results from the fact that by purchasing the required CNC mechanisms or installing the equipment into existing robots it is relatively easy and inexpensive to create a MAM system with capability of producing large size parts in short time spans.

Gas metal arc welding GMAW, in which an electric arc is established between the tip of a consumable wire (electrode) that is fed automatically through a nozzle into the weld pool under the protection of inert or active shielding gases, is the most widespread technology utilized in WAAM, under the designation of gas metal arc direct energy deposition (GMA-DED) (Williams et al., 2016) (Fig. 5c). This is attributed to the fact that GMA-DED is the simplest and cheapest process to implement due to its direct wire-feeding, which is coaxial with the nozzle of the welding torch.

The other two WAAM-based processes included in Fig. 3; gas tungsten arc direct energy deposition (GTA-DED) (Baufeld et al., 2010) and plasma arc direct energy deposition (PA-DED) (Martina et al., 2012), use electric arcs that are formed between a non-consumable electrode (typically made of tungsten) and the metal part under construction (Figured 5 d and 5e). The working principles of these two processes are retrieved from gas tungsten arc welding (GTAW) and plasma arc welding (PAW) equipment (Wu et al., 2018) and, therefore, the feedstock wire is not supplied through the nozzle as in the case of GMA-DED, but through an additional wire feeding unit.

Because the electric arc in PA-DED has greater energy concentration, better stability and less thermal distortion than in GTA-DED, the deposition rates are higher than those in GTA-DED. In fact, PA-DED remains as the only electric arc-based MAM process that can also use powder as feedstock (Zhang, 2003).

3. Hybrid manufacturing

Researchers have been struggling over the proper definition to be given to the term ‘hybrid manufacturing’ since its use started to be widespread in the late 1990's. Rajurkar et al. (1999) defined ‘hybrid machining’ as a combination of two or more material removal processes. Because this description was somewhat vague due to the fact that combinations of two or more material removal processes are intrinsic to most subtractive manufacturing routes, Kozak and Rajurkar (2000) decided to readjust the definition by requiring the performance characteristics of hybrid machining processes to be considerably different from those of the individual processes when performed separately.

Aspinwall et al. (2001) further enhanced the definition of ‘hybrid machining’ by considering that a combination of two or more material removal processes could only be considered ‘hybrid’ if they were applied independently on a single machine. In case the material removal processes were applied simultaneously, the integration should rather be named as ‘assisted’.

In parallel with these initial attempts to define ‘hybrid machining’, the metal forming community was also using the term ‘hybrid’ to characterize manufacturing routes built upon the combination of different forming processes such as, for example, extrusion and electromagnetic forming (Jäger et al., 2011).

In the early 2010's, the awareness that the term ‘hybrid manufacturing’ should be used in a broader perspective to include other processes than machining led some authors to associate ‘hybrid manufacturing’ to the fundamentals of each combined process, namely to the different forms of energy that are used at the same time in the same processing zone (Nau et al., 2011).

In recognition of this, the International Academy for Production Engineering (CIRP) proposed a definition of hybrid manufacturing processes as those ‘based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process performance’. However, subsequent debate about the wording ‘simultaneous and controlled interaction’ requiring the process mechanisms and/or energy sources/tools to interact more or less in the same processing zone and at the same time gave rise to the following two subsequent definitions of hybrid manufacturing (Zhu et al., 2013):

(a) A narrow definition of hybrid manufacturing based on the previous definition requiring different process mechanisms to be used in the same processing zone;
(b) An open definition of hybrid manufacturing based on the combination of two or more established manufacturing processes into a new combined set-up.

The narrow definition looks at hybrid manufacturing from a concurrent point of view, in which two or more processes are combined in-situ at the same time. The open definition looks at hybrid manufacturing from a process sequence point of view and is strongly related to the gains of employing innovative combined manufacturing approaches instead of traditional manufacturing routes. Also, the combined processes no longer require to be based upon dissimilar technologies, as shown by Araghi et al. (2009) who successfully integrated stretch forming and incremental forming (i.e. two plastic deformation processes), into an innovative hybrid set-up.

Revisitation of the above-mentioned definitions by Lauwers et al. (2014), resulted in the classification of hybrid manufacturing in two main groups (Fig. 6a). The first group (labelled as ‘I’) recovers the narrow (concurrent) view of hybrid manufacturing and contains processes where two or more energy sources/tools are combined and have a synergetic effect in the processing zone. The group is further divided into two

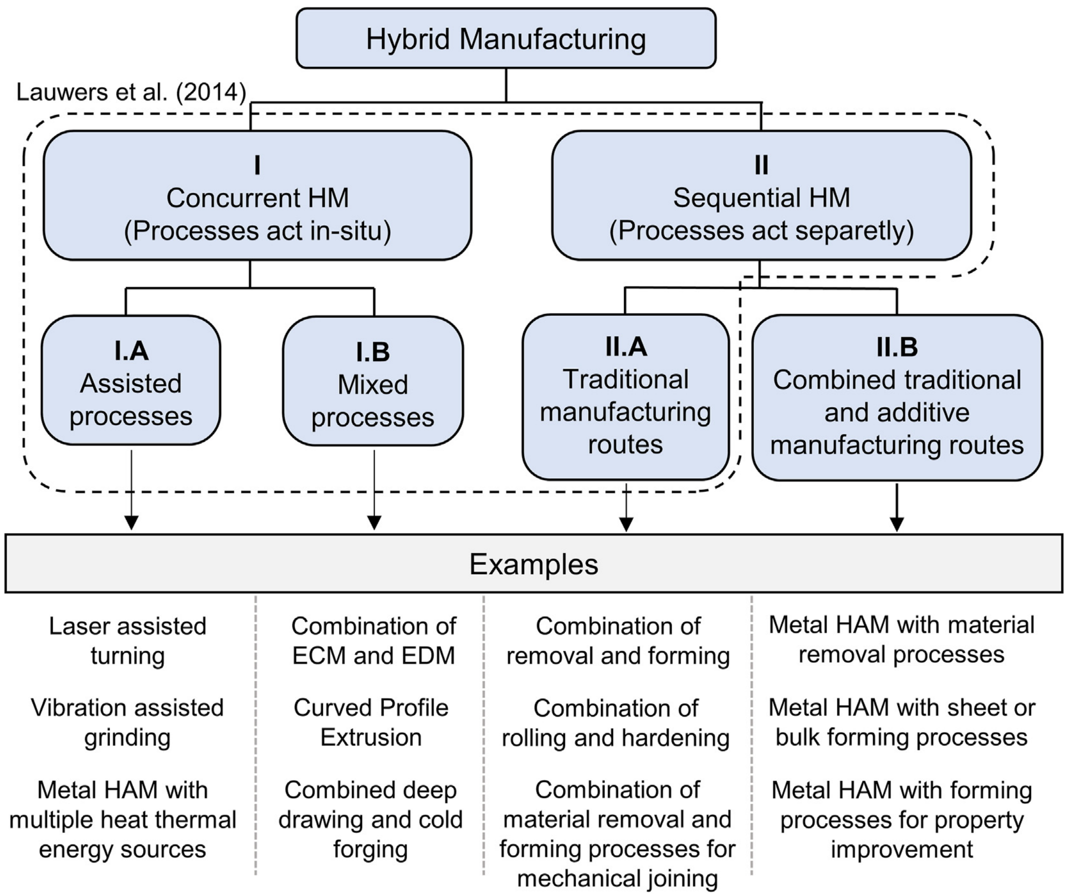

Fig. 6. New extended proposed classification of hybrid manufacturing processes built upon that originally proposed by Lauwers et al. (2014) (refer to black dashed region).

subgroups: I.A – containing the assisted processes, in which a secondary process is priory utilized for assisting the primary process in-situ, and I.B – containing the mixed processes, in which two or more processes are simultaneously employed.

The second group (labelled as 'II') is related to the open definition of hybrid manufacturing and accounts for the processes where the synergetic effects are obtained by controlled combination of processes acting separately in order to fabricate parts in a more efficient and productive way. The combination of boss forming and upsetting to connect a sheet to the end of a tube (Alves et al., 2018) and the combination of partial cutting, bending and sheet-bulk forming to produce lap joints in metal sheets (Pragana et al., 2018) are two examples belonging to this group.

As discussed above, we can conclude that the classification of hybrid manufacturing shown in Fig. 6 evolved from the original concept exclusively focused on machining to a broader concept that includes other manufacturing processes and routes. However, the roots behind the original classification by Lauwers et al. (2014) (refer to the dashed region in Fig. 6) are deeply associated to the utilization of primarily processed raw materials in the form of ingots, plates, sheets, rods, tubes, profiles, powders, pellets, etc …

Taking into consideration the emergence of novel hybrid manufacturing routes built upon the utilization of additively deposited materials via combination of additive and traditional manufacturing processes to fabricate parts that are difficult (or, even impossible) to be obtained by each of the processes separately, there is a necessity of modifying the original classification of Lauwers et al. (2014) to include two new subgroups II.A and II.B (Fig. 6).

The subgroup II.A includes the controlled application of process mechanisms on primarily processed raw materials. The subgroup II.B, hereafter designated as hybrid additive manufacturing (HAM), contains the controlled application of process mechanisms on additively deposited materials and the controlled application of additive manufacturing on primarily processed raw materials previously subjected to traditional manufacturing processes.

The vision behind this new classification paves the way for the hybridization of additive manufacturing with traditional manufacturing processes with the goal of increasing its applicability domain and overcoming its limitations related to low productivity, rough surface quality and lack of dimensional precision (Table 1). Conversely, hybridization of additive manufacturing may also serve to add flexibility and foster new applications of traditional manufacturing processes/routes.

The third part of this paper will be focused on metal hybrid additive manufacturing (hereafter abbreviated as 'metal HAM') with special emphasis on the combination of metal additive manufacturing (MAM) with forming processes.

4. Metal hybrid additive manufacturing

4.1. Metal HAM with multiple thermal energy sources

Metal hybrid additive manufacturing based on the utilization of multiple thermal energy sources belongs to the group I.A (assisted processes) of Fig. 6 because the thermal energy sources only assist the primary additive manufacturing process. The idea started to attract attention in the mid 2000's and has roots on the development of novel hybrid welding processes capable of overcoming the limitations of laser welding regarding gap restrictions, damage of coatings and blowhole formation within the molten material (Ono, 2002), by assisting the laser with an electric arc.

The concept of using multiple thermal energy sources was,

Table 1
Dimensional tolerances of additive manufacturing and other forming and machining processes (adapted from Nielsen and Martins, 2021).

Manufacturing process	ISO IT Tolerance grade (ISO 286)														
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Hot forging (impression-die)													■	■	■
Hot forging and sizing (near-net shape forming)									░	■	■	■			
Warm forging									░	■	■				
Cold forging (precision forming)						░	■	■	■						
Turning					░	■	■	■	■	■					
Milling								░	■	■	■				
Grinding			░	■	■	■									
Honing			■	■											
Lapping		■	■												
Additive manufacturing										■	■	■	■	■	■

Standard range ■ Under favourable conditions ░

eventually, implemented in the field of MAM to increase process stability by providing supplemental energy. Qian et al. (2006), for example, proposed the utilization of a laser to assist plasma arc direct energy deposition (PA-DED) systems. Zhang et al. (2006) evaluated this new hybrid manufacturing assisted process, known as 'laser-plasma deposition manufacturing', and concluded about its capability in obtaining rapid thick and uniform coating deposition, and better mechanical properties than those offered by the original (non-assisted) PA-DED systems.

More recently, Zhang et al. (2018) developed a laser assisted GMA-DED system for building thin-walled aluminum specimens and proved the effectiveness of the concept in controlling the height and uniformity of the wall width (Fig. 7a). Other researchers focused on evaluating and analyzing the performance of this new hybrid additive manufacturing process regarding its microstructure (Liu et al., 2020) and deposition strategy (Li et al., 2020).

Wu et al. (2020), utilized a laser assisted GTA-DED variant to build aluminum specimens (Fig. 7b), which revealed good microstructure and mechanical properties, and smaller incidence of cracks and pores when compared with specimens built by other AM processes.

4.2. Metal HAM with material removal processes

The hybridization of metal additive manufacturing (MAM) with material removal processes (also known as, 'subtractive processes') can be grouped into two different categories:

(a) Utilization of material removal processes at post-processing level in order to obtain the geometry precision, the dimensional tolerances and the surface quality required for the built part;
(b) Integration of material removal processes during a manufacturing sequence to obtain parts that would be impossible, (or very difficult and expensive), to produce individually either by additive manufacturing or by material removal operations.

The first category will not be considered in this paper because post-processing material removal operations are intrinsic to the majority of metal additive manufacturing (MAM) routes in order to ensure that the built parts meet the design specifications. One, among many examples, is the removal of the 'stair-case' profile of metal built parts shown in Fig. 8a.

This type of integration has been long recognized and is embodied in the availability of hybrid manufacturing systems with combined milling/turning and MAM capabilities for producing ready-to-use complex metal built parts, using a single clamping, in small lead times (Lorenz et al., 2015; Merklein et al., 2016).

Although this category can be considered the simplest, it is impossible to underestimate its importance in lowering the overall material and energy consumption. This is further recognized in case of processing expensive and difficult-to-work materials such as titanium or nickel-based super alloys because the reduction of the buy-to-fly (BTF) ratio (Fig. 8b), which is the ratio of the mass of the initial workpiece to the one of the finished part, ensured by the hybridization of metal additive manufacturing (MAM) with material removal at post-processing level is

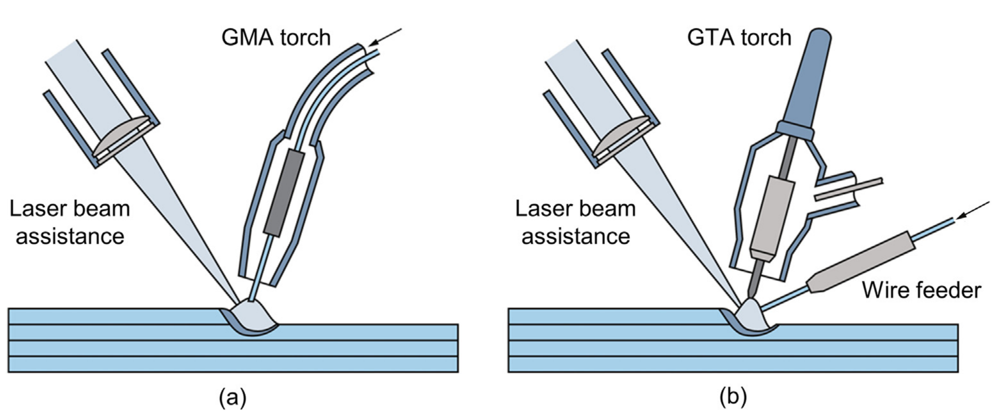

Fig. 7. Schematic representation of metal additive manufacturing in which (a) GMA-DED and (b) GTA-DED systems are assisted by a laser thermal energy source.

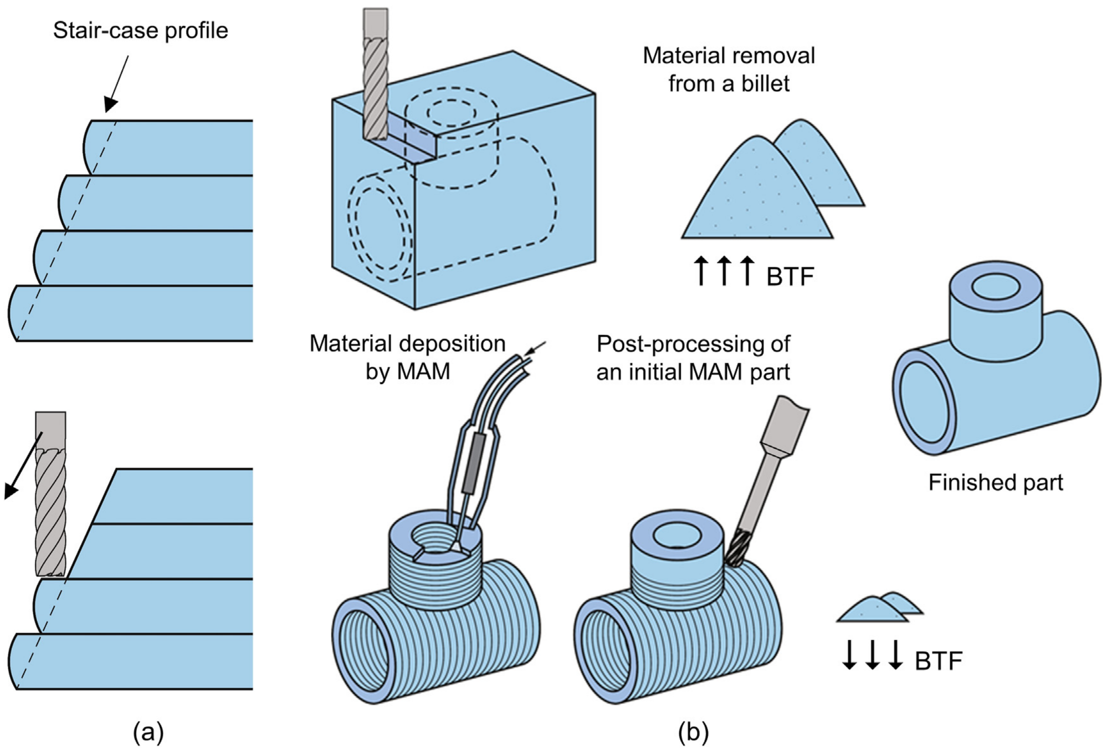

Fig. 8. (a) Schematic representation of the utilization of metal removal processes at post-processing level to eliminate the 'stair case' profile of metal built parts, and (b) comparison of BTF ratios for a traditional metal removal process and a hybrid additive manufacturing process with material removal.

very effective in lowering the overall manufacturing cost and material waste (Seow et al., 2019).

The second category allows producing a wide variety of complex parts with intricate features but also includes simple parts as that shown in Fig. 9. In fact, the attempt of using metal removal operations at 'post-processing level' (i.e. after conclusion of the MAM cycle) in the built part shown in Fig. 9 is not feasible due to restricted cutting tool access. In cases like this, machining of the overhanging edges, shallow sections or complex features must be carried out in conjunction with material deposition during the manufacturing route (Luo and Frank, 2010).

The integration of metal additive manufacturing with material removal processes from the perspective of the above-mentioned second category began in the mid 1990's. Fessler et al. (1996) and Klock et al. (1996) combined an earlier type of L-DED system consisting of a laser with a coupled powder feeding system, (an equipment that was widely used for laser cladding at the time), with a high-speed milling machine to perform material removal operations at intermediate stages of metal deposition.

However, research in metal HAM with material removal only began to expand and consolidate in the mid 2000's through customization of either the MAM processes and/or the material removal operations. Kerschbaumer and Ernst (2004), for example, revisited the earlier concepts and provided further insights in tool path generation, performance of the laser power source and powder feeding customization strategies. Sreenathbabu et al. (2005) integrated GMA-DED into a CNC milling system for machining irregular layers into a more precise planar shape. Song et al. (2005) assembled two GMA torches and a laser in a milling machine to obtain a hybrid multi-tasking system capable of delivering a more precise and selective metal deposition by means of an automated AM tool-switching facility.

In the same line of developing hybrid multi-tasking systems, Kovacevic and Valant (2006) patented a six-axis robot system for building metal parts with plasma and laser-based deposition capabilities. Xinhong et al. (2010) developed a system combining PA-DED additive manufacturing and milling to fabricate an aeroengine double helix integral impeller made from a nickel super alloy.

These examples and others not mentioned above, stimulate the machine tool industry to develop and commercialize the first hybrid additive manufacturing systems in the earlies 2010's. DMG Mori introduced the LASERTEC 65 3D Hybrid system that combines material deposition by L-DED (a laser head with material deposition through a coaxial nozzle) with a full 5-axis milling machine (Woodcock, 2014). Mazak introduced the Integrex i-400 a.m. also based in the combination of L-DED with 5-axis machining capabilities (Hybrid Manufacturing Technologies, 2014).

In fact, most of the available in-house and commercial hybrid additive manufacturing systems are nowadays based on DED technology due to its greater flexibility for combining additive and subtractive processes into a single machine (Manogharan et al., 2015).

The first hybrid additive manufacturing system based on PBF technology was the Lumex Avance-25 byMatsuura (2020). The system combines material deposition by LPBF with high-speed milling and is gaining attention for its potential of perfecting external contours, surface roughness and corrosion characteristics in dies and molds (Ahn, 2011).

In an effort to increase flexibility of metal deposition the company 3D-Hybrid (2020) is nowadays offering the possibility of integrating GMA-DED, L-DED and cold spray heads (commonly used in coating applications) into CNC machining centers.

4.3. Metal HAM with forming processes

The hybridization of metal additive manufacturing (MAM) with forming processes in which medium or large batches of semi-finished parts are produced by forming and additional functional elements are subsequently added by additive manufacturing, is recognized as an effective approach for extending the conventional forming process routes into the fabrication of tailor-made, customer-oriented, products (Merklein, 2016).

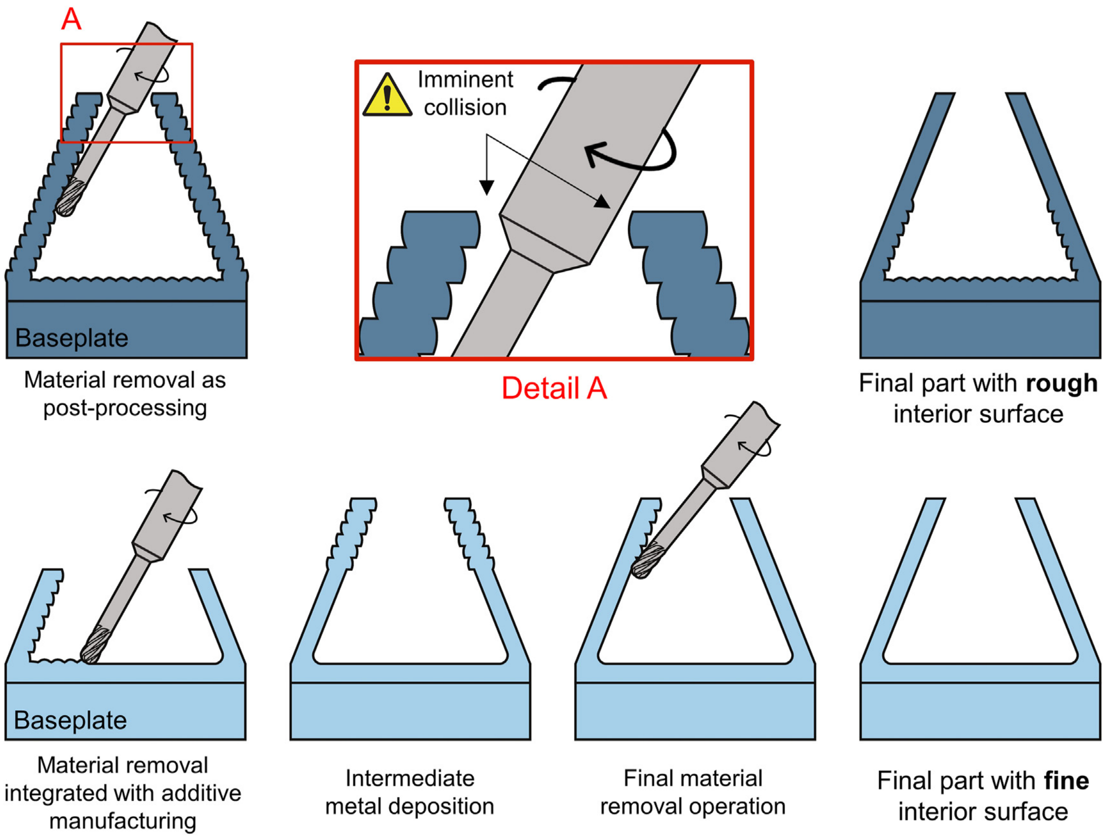

Fig. 9. Combination of metal additive manufacture and material removal during the fabrication sequence to allow building the final metal part.

Another aspect in metal HAM with forming processes is the construction of preforms with optimized geometries by additive manufacturing to ensure defect-free flow and die filling with minor metal losses during small batch, single-stage, forming operations (Silva et al., 2017).

Finally, there is also the possibility of combining MAM with forming processes to improve the properties of the deposited metals both during and at the end of a process route. In connection to this it is worth mentioning that the utilization of MAM to improve the surface of forming tools (e.g. improve hardness, wear and oxidation resistance of tools) (Hofmann et al., 2015) is not considered here because it does not fit within the definition of hybrid manufacturing given in Section 3. The fabrication of metal forming tools by additive manufacturing (Juncker et al., 2015) is not, for the same reasons, included in what follows.

Taking into consideration the previous framework, authors decided to group the combination of metal additive manufacturing (MAM) with forming processes into four different categories:

- Integration with processes to improve the properties of the deposited metals;
- Integration with bulk forming processes;
- Integration with sheet forming processes;
- Integration with joining by forming processes;

4.3.1. *Integration with processes to improve the properties of the deposited metals*

The roots of combining metal hybrid additive manufacturing (metal HAM) with processes to improve the properties of the deposited metals are found in mechanical surface treatments. The first integration to be considered in this section finds additional roots on the application of pressure along the weld beads produced by friction stir welding as a mean of controlling residual stresses and distortions (Altenkirch et al., 2009). This process, hereafter designated as 'surface rolling', subjects the weld bead surfaces to plastic deformation by means of a hard and highly polished roller in order to improve surface finish and induce compressive stresses that will counteract the residual stresses originated from the heating-cooling cycles of welding.

Colegrove et al. (2013) performed the first application of surface rolling to the successive deposited layers of WAAM-based processes (Fig. 10). The procedure was carried out after each new layer had cooled to near-ambient temperature and results demonstrated its positive influence on the reduction of residual stresses and distortion but also on the final microstructure, due to a reduction of grain size caused by dynamic recrystallization induced by plastic deformation.

Zhang et al. (2013) encompassed a different strategy for the application of pressure on the deposited layers of WAAM-based processes by focusing on the in-situ utilization of the roller directly behind the deposition torch.

In a subsequent investigation, Colegrove et al. (2017) revealed the positive influence of surface rolling on the mechanical properties (yield strength, ultimate tensile strength and elongation) of the deposited materials due to modification of undesirable columnar microstructures (the main contributors for anisotropic behavior) into refined equiaxed microstructures.

Another type of integration of metal additive manufacturing (MAM) with processes aimed at improving the properties of the deposited metals is the utilization of shot peening on the successive layers of WAAM-based processes for relieving residuals stresses and minimizing distortions (Prinz and Weiss, 1993). In shot peening the surface of each deposited layer is impacted repeatedly with small hard balls to cause plastic deformation and compressive stresses, but contrary to surface rolling it causes no considerable variation in the overall shape of the deposited layers.

Bamberg (2012) extended the utilization of metal HAM with shot peening by proposing the combination of L-DED with other variants of

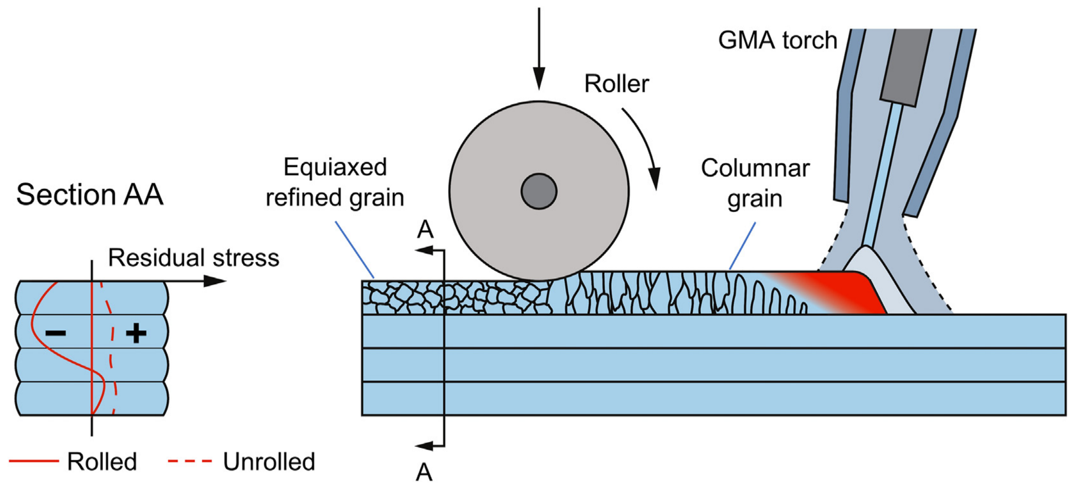

Fig. 10. Schematic representation of a hybrid metal additive manufacturing process resulting from combination of WAAM with surface rolling. Emphasis is given to the modification of the metallurgical structures (reduction of grain size and its effect on residual stresses).

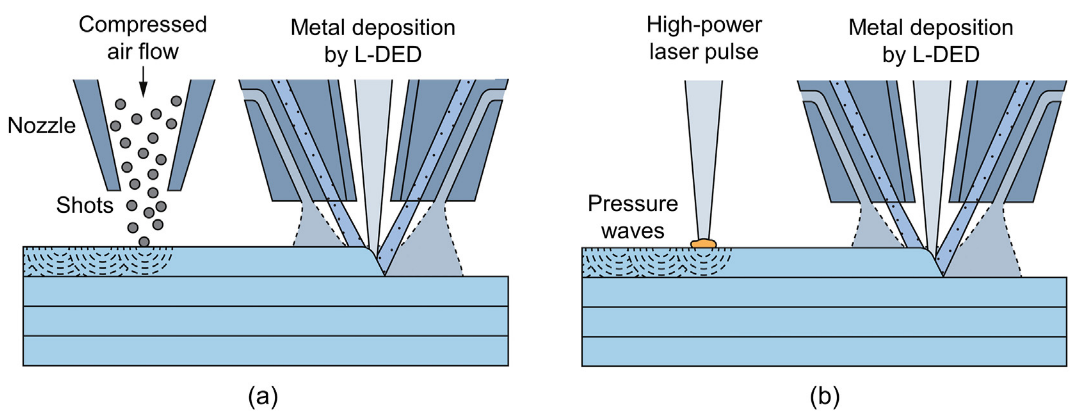

Fig. 11. Schematic representation of a hybrid metal additive manufacturing process resulting from combination of L-DED with (a) shot peening and (b) laser shock peening.

shot peening (Fig. 11a) such as ultrasonic or laser shock peening, based on the utilization of high-frequency oscillations from piezoelectric transducers or laser pulses from high-power lasers (Fig. 11b), respectively. The author claimed its utilization for hardening selective areas of additively manufactured blade elements of gas turbines for aircraft engines.

In recent years metal HAM with peening has grown significantly as a mean of enhancing the properties of built parts for applications in military, aerospace, automotive and biomedical industries (Sealy, 2018).

Another advantage in metal HAM with peening is the improvement of fatigue life due to the effect of compressive stresses on delaying the initiation of fatigue cracks. Uzan et al. (2018), for example, investigated the effect of shot peening on the fatigue resistance of aluminum alloy specimens produced by LPBF and concluded about its positive effect on the fatigue resistance and fatigue limit. Fractography of the cracked specimens also revealed that for shot peened specimens, the site of fatigue crack initiation was deeper than that of specimens that had not undergone shot peening after LPBF.

Sokolov et al. (2020) recently proposed the integration of MAM with hot rolling as a thermomechanical post-treatment solution for large-scale parts of titanium alloys produced by L-DED. Results disclosed by the authors, confirmed advantages in decreasing residual porosity and inducing microstructural changes in the deposited material that contributed to improve the ultimate tensile strength and the elongation at break.

The combination of MAM with hot forging through the utilization a customized WAAM torch was recently proposed by Duarte et al. (2020) as an alternative solution for decreasing residual porosity, refining the microstructure and improving the mechanical properties of the deposited material. The customized torch is equipped with a hammer placed inside the gas nozzle that is activated by a vibrating actuator for locally performing in-situ plastic deformation of the deposited material at high temperature (Fig. 12).

4.3.2. Integration with bulk forming processes

The first applications in metal HAM with bulk forming processes were made by Silva et al. (2017), Sizova and Bambach (2017) and Zhang et al. (2017). Silva et al. (2017) investigated the formability of an aluminum alloy AA5083 deposited by WAAM (GMA-DED) by means of upset formability tests on cylindrical and tapered specimens machined out from the deposited material. Results confirmed the excellent ductility of the deposited material, which showed a fracture locus in the principal strain space similar to that of wrought (commercial, fully dense) test specimens made from the same aluminum alloy.

Silva et al. (2017) also carried out an experimental and numerical analysis of a cold heading operation performed on a deposited preform of the same aluminum alloy that confirmed previously fracture locus and showed that compressive dominant stress states commonly found in bulk forming promote the closure of voids (i.e. increase of relative density) and improve the properties of the deposited material through strain hardening (Fig. 13).

Sizova and Bambach (2017) investigated the high temperature

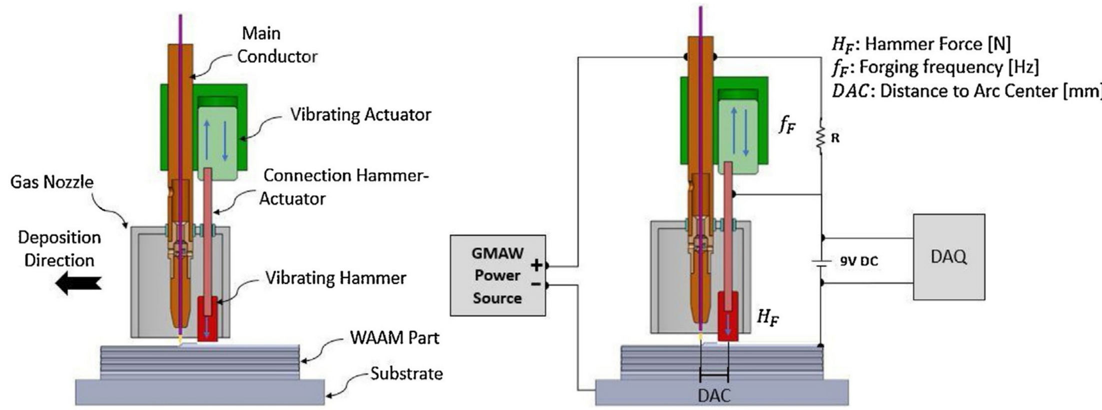

Fig. 12. Schematic representation of the customized torch equipped with a hammer placed inside the gas nozzle and of the main electrical scheme (Duarte et al., 2020).

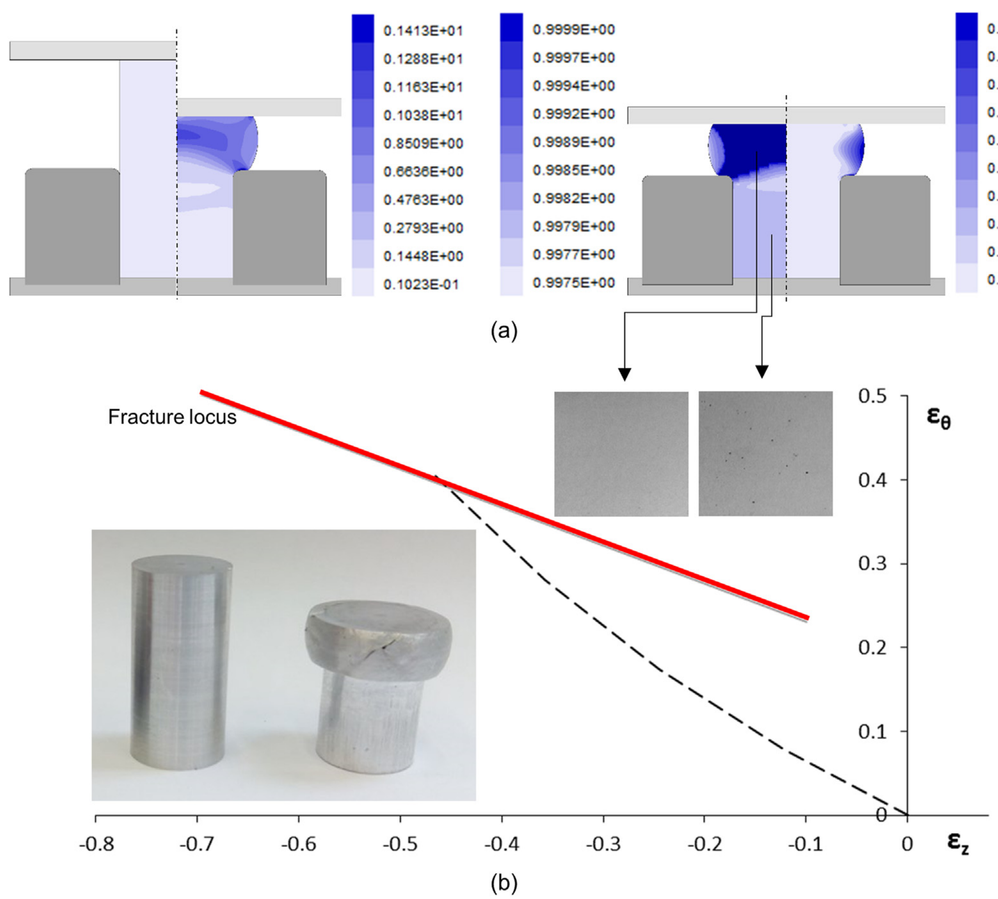

Fig. 13. Cold heading of a preform made from a deposited aluminum alloy AA5083 (adapted from Silva et al., 2017).

(a) Finite element computed distributions of effective strain, relative density and ductile damage at the instant of deformation where cracks are triggered;
(b) Evolution of the strain loading path up to fracture in the principal strain space.

deformation behavior of Ti–6Al–4V deposited by LPBF by compressing cylindrical test specimens after heat-treatment and analyzing the evolution of microstructure. Results showed that the microstructure of the deposited material could be refined during hot working and allowed authors to conclude that complex forgings of titanium could in the future be manufactured in a single forging stage using shape-optimized preforms produced by additive manufacturing.

Zhang et al. (2017) also focused on the high temperature deformation behavior of Ti–6Al–4V deposited by LPBF to investigate the influence of strain and strain rate on the evolution of microstructure, porosity, and micro hardness. The experiments were carried in a Gleeble testing machine and results showed that compression improved the microstructure, decreased the porosity by values up to 75% and decrease the anisotropy of the deposited material.

Papke et al. (2018) investigated the formability of a stainless steel 316 L deposited by LPBF by means of compression tests. The comparison with results obtained from wrought (commercial, fully dense) test specimens showed that although no significant differences were found in the hardness of the preforms, the layer-wise structure of the deposited material had a significant influence in material flow and justified the differences in the formability of deposited and wrought materials for strain values above 0.2.

Hirtler et al. (2018) utilized a WAAM (GMA-DED) system installed in a robot to analyze the possibility of adding functional elements by additive manufacturing on semi-finished parts produced by forging. For this purpose, aluminum AlSi12 was deposited on top of a T-section forged from a round bar of EN-AW 6082 in an attempt to decrease the number of forging stages, diminish material wastage, and reduce tool wear and forging defects caused by the extensive plastic deformation associated to the fabrication of high ribs by conventional forging. Results demonstrated the overall feasibility of the hybrid manufacturing route, but further investigation was claimed to be necessary for enhancing material bonding of the first additive manufactured material layer.

In a subsequent publication, Bambach et al. (2020) performed a similar work on titanium for demonstrating the feasibility of the above-mentioned hybrid manufacturing route in difficult-to-process materials. A second example consisting of a titanium turbine blade was included to validate the feasibility of using additive manufacturing to produce preforms for subsequent forging operations.

Meiners et al. (2020) revisited the possibility of adding functional elements by additive manufacturing on semi-finished parts produced by forging by considering material deposition by WAAM and L-DED on a forged T-section (Fig. 14). They concluded that higher deposition rates of WAAM are advantageous for hybrid manufacturing of Ti–6Al–V4 aerospace forgings due to benefits in both manufacturing costs and processing time.

Another type of metal HAM with bulk forming was recently proposed by Michl et al. (2020), who utilized WAAM (GMA-DED) installed in a robot to produce annular preforms of deposited mild steel ER 70 S-6 with optimized mass distribution for subsequent ring rolling. They concluded that combination of WAAM with ring rolling is viable to improve efficiency and costs in complex ring rolled parts due to elimination of the upsetting, profiling and piercing operations that are utilized to produce the annular preforms in conventional manufacturing routes (Fig. 15).

The combination of additive manufacturing with coining was also recently proposed as a novel process route to fabricate high value-added collector coins (Fig. 16) (Pragana et al., 2020a; Pragana et al., 2020c). The cylinders from which the coin blanks are obtained are built by LPBF along the z-axis to minimize the use of support structures and to improve the overall efficiency and quality of the material deposition. Wire electro-discharge machining and surface polishing are utilized to slice the cylinders into individual coin blanks with appropriate quality requirements. The coin blanks are then compressed (coin minting) between dies in a press-tool to impart lettering and other reliefs on both surfaces.

The utilization of additive manufacturing as an alternative to conventional rolling, blanking and edge rimming, allows producing coin blanks with complex intricate contoured holes, which are very difficult or even impossible to manufacture by blanking, laser cutting or water jet. The new hybrid manufacturing route allows producing collector coins that are disruptively different from those that are nowadays available in the market.

4.3.3. Integration with sheet forming processes

The integration of metal additive manufacturing (MAM) with sheet forming processes comprises combinations with bending, deep drawing, spinning and incremental sheet forming.

4.3.3.1. Bending. Regarding metal HAM with bending, most of the published works have been focused on incorporating three-dimensional functional features on flat sheets. Silva et al. (2017) and Li and Rapthadu (2017) proposed hybrid additive manufacturing routes in which a sheet is bent and three-dimensional features are added by deposition with WAAM followed by machining. In case the accessibility to the region of the sheet where the features are to be added is limited by gravity constrains of the deposition torch and/or by accessibility constrains of the cutting tool, Li and Rapthadu (2017) proposed the sheet to be first bent into an intermediate configuration, where the features can be easily added, and subsequently bent to the final configuration. They concluded that the hybrid approach can provide additional geometry creation capabilities and better accessibility to additive manufacturing (Fig. 17).

Butzhammer et al. (2017) investigated the possibility of adding features on a Ti–6Al–V4 sheet by LPBF before or after sheet bending. They concluded that adding the features before bending leads to a reduction in formability, but they also observed that adding the features after bending is challenging due to the irregularities available on the bent sheet surfaces. Shear destructive tests for evaluating the connection strength between the deposited features and sheets revealed that adding the features before or after bending does not influence the connection strength between the two parts, which is higher than that of a monolithic machined part of identical geometry subjected to bending.

In a subsequent work, Papke et al. (2018a) investigated the influence of the stress state resulting from the bending operation on the connection strength between the deposited features and sheets. They considering features created on the compression and tension sides of a bent sheet and concluded that the connection shear strength is lower in case of features added on the compression sides.

Rosenthal et al. (2019), (Rosenthal et al., 2019a), (Rosenthal et al., 2020) performed an investigation on the bending of additively manufactured (LPBF) flat monolithic sheets of Hastelloy X. Results allowed concluding that additive manufactured semi-finished sheets can be successfully used in subsequent forming operations and numerical simulation can be carried out in a manner identical to that performed in

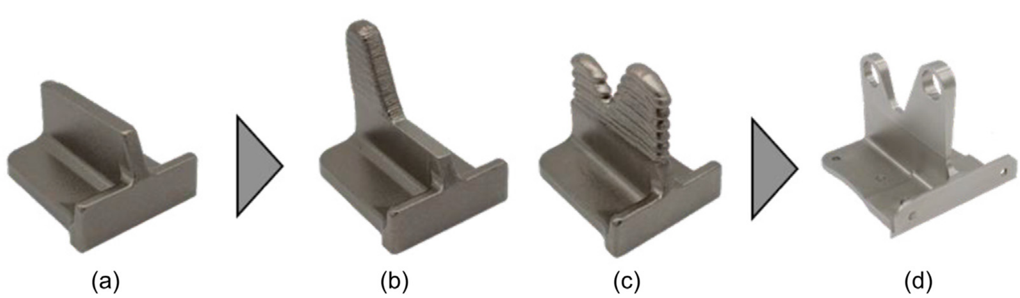

Fig. 14. Integration of metal additive manufacturing with forming by depositing Ti–6Al–V4 on top of a T-section forged from a round bar of the same material (Meiners et al., 2020).

(a) Forged T-section;
(b) Forged T-section with added L-DED layers;
(c) Forged T-section with added WAAM layers;
(d) Final machined part.

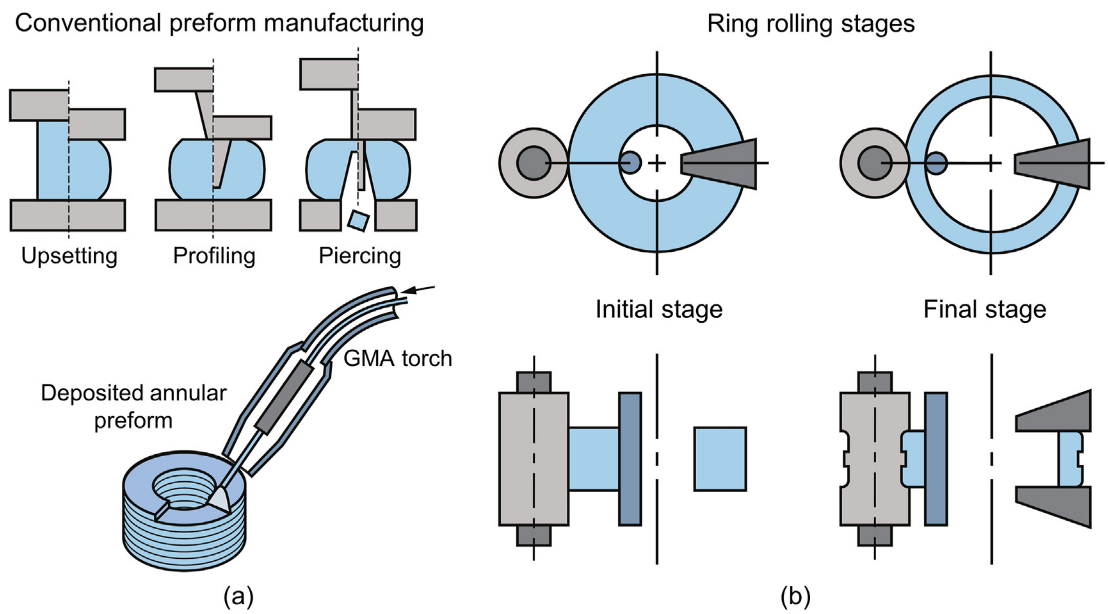

Fig. 15. (a) Schematic comparison of conventional manufacturing and additive manufacturing routes to fabricate annular preforms for ring rolling, and (b) front and top view of the initial and final stages of the ring rolling operation.

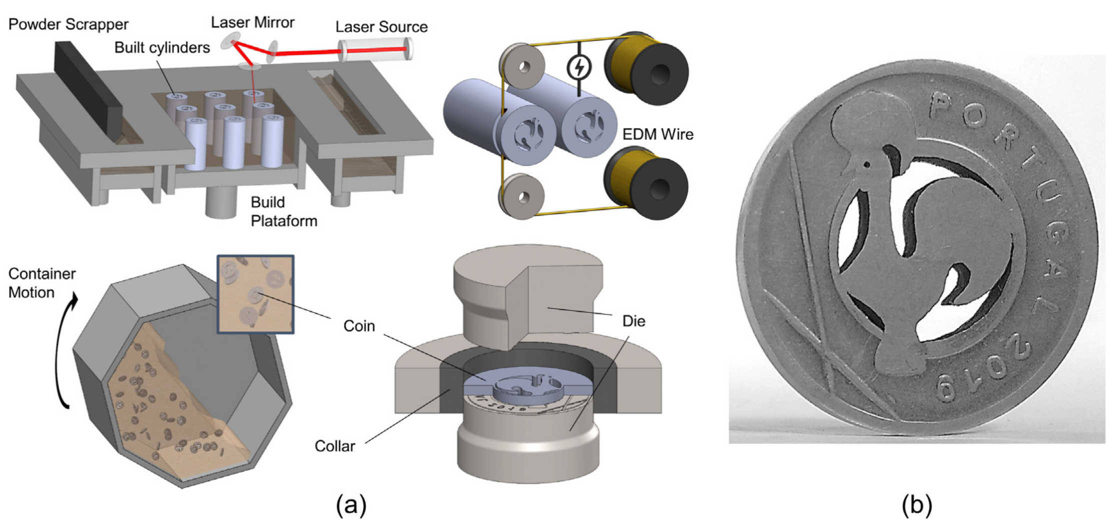

Fig. 16. Integration of metal additive manufacturing with coin minting (adapted from Pragana et al., 2020a).

(a) Schematic representation of the new hybrid manufacturing route combining deposition by LPBF, wire electro discharge machining, polishing and coin minting;
(b) Photograph of a coin sample made from AISI 316 L.

anisotropic wrought sheets but using an anisotropic Drucker-Prager yield criterion to capture the tension-compression asymmetry of the deposited material. They also concluded that the material behavior is different from that of wrought rolled sheets because it is highly influenced by the thermal history of the additive manufacturing process.

4.3.3.2. Deep drawing. Metal HAM with deep drawing has been mainly focused on incorporating features in drawn sheets or constructing blanks for subsequent drawing operations. Ahuja et al. (2015) were among the first researchers to integrate metal additive manufacturing with deep drawing and utilized LPBF to add cylindrical features on top of pre-drawn and drawn titanium sheets (Fig. 18). They developed a customized clamping mechanism for attaching the drawn sheet inside the LPBF system and tested the bonding resistance between the deposited features and the sheets by means of destructive shear tests. The low shear resistance values obtained for the cylindrical features constructed on the deep drawn sheets were attributed to uneven powder distribution causing un-melted areas, which were confirmed by means of scanning electron microscopy analysis, and to changes in local heat conduction resulting from the geometry and condition of the deep drawn sheet surfaces.

Bambach et al. (2017) evaluated two different hybrid additive manufacturing (HAM) routes based on the combination of tailored laser cladding by L-DED and deep drawing, with the objective of improving the performance, saving weight and reducing the risk of excessive thinning or fracture:

(a) Increase the stiffness of deep drawn sheets through local reinforcement by tailored laser cladding instead of using thicker blanks;
(b) Reinforce the critical thickness sections of the blanks by tailored laser cladding prior to hole-flanging.

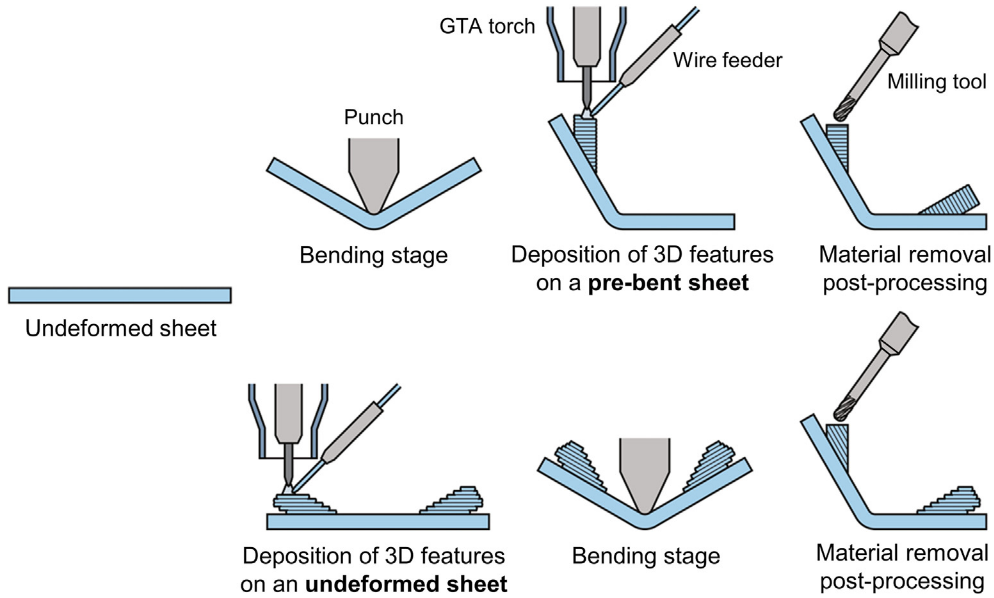

Fig. 17. Schematic representation of the addition of three-dimensional features by LBPF before and after sheet bending (adapted from Li and Rapthadu, 2017).

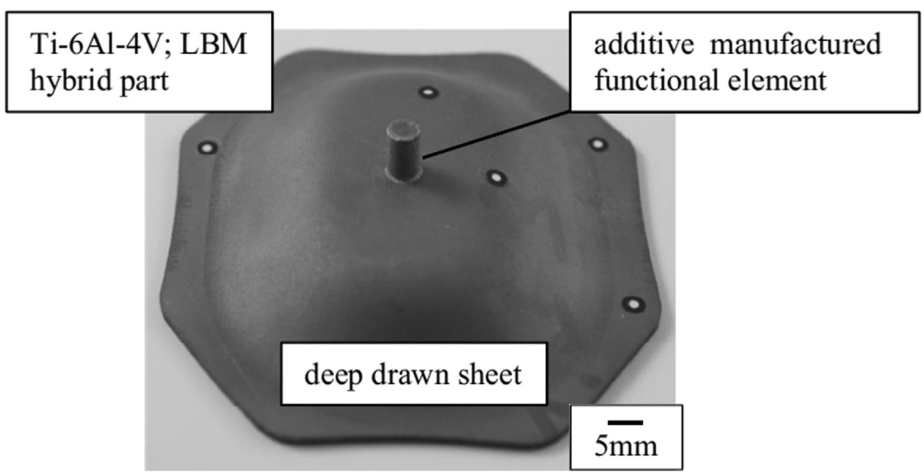

Fig. 18. Integration of metal additive manufacturing with deep drawing to add a cylindrical feature on top of a deep drawn titanium alloy sheet (Merklein et al., 2016).

Destructive tests on specimens produced by the first hybrid manufacturing route revealed an increase in stiffness of 95% when compared to conventional (non-reinforced) specimens, while only accounting for 6% increase in weight. The result is interesting for lightweight construction design and fosters the utilization of tailored laser cladding as an effective, low cost, alternative to the use of tailor blanks (Fig. 19).

Limited formability in hole expansion due to the occurrence of cracks

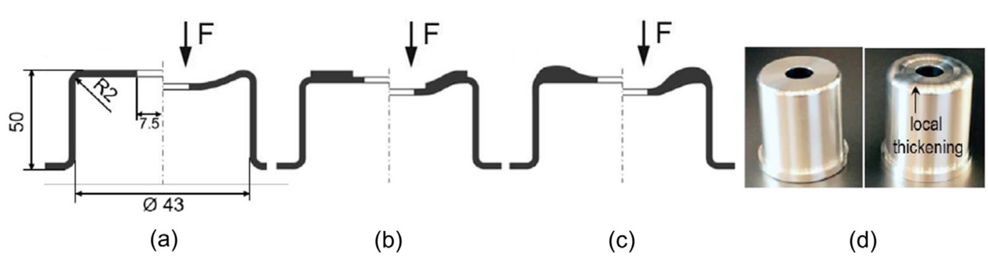

Fig. 19. Local reinforcement to minimize deflection of a deep drawn component subjected to a force (Bambach et al., 2017a).

(a) Geometry of the original deep drawn component.
(b) Local reinforcement by means of welded, soldered or glued patchwork blanks;
(c) Local reinforcement by tailored laser cladding;
(d) Photograph of the original and tailor laser cladded components.

around the radius of the flanges led the authors to anticipate difficulties in using tailor laser cladded blanks as semi-finished products for subsequent sheet forming operations. Still, authors claimed that plastic deformation of the clad reinforcements is viable up to some extend and will benefit from the superimposition of pressure.

A similar approach by Schulte et al. (2020) allowed the fabrication of deep drawn components having various teeth geometries from orbital formed tailored blanks with local material deposition by LPBF.

The influence of additively manufacture elements on sheet formability was recently revised by Hafenecker et al. (2020) who varied the geometry and number of three-dimensional cylindrical pins deposited on a blank and performed a combined theoretical and experimental investigation to quantify the influence of the pins on the overall formability.

4.3.3.3. Incremental sheet forming. Hölker et al. (2014) were the first to propose the integration of additive manufacturing, single point incremental forming and material removing in a single machine, using a single clamping.

Lopez et al. (2018) performed single point incremental forming of aluminum AlSi10Mg sheets produced by LPBF and measured the evolution of the residual stresses on the inner and outer surfaces of the sheets during the forming process. In a subsequent work, Ambrogio et al. (2019) revisited the utilization of additive manufacture to locally reinforce commercial sheets (Bambach et al., 2017a) and proposed the utilization of LPBF to deposit tailored layers of material in selected regions of the blanks to be used in single point incremental forming. Results confirmed the advantages of tailored sheets regarding geometric accuracy and reduction of sheet thinning in the regions subjected to more pronounced plastic deformation, widening its applicability domain to more complex shapes.

A recent investigation by Pragana et al. (2020b) on single point incremental forming of AISI 316 L stainless steel sheets produced by WAAM allowed concluding that although the formability of the deposited sheets was smaller (with major principal true strains reduced by nearly 67%) than that of commercial sheets made from the same material, it is still appropriate to withstand large plastic deformations (Fig. 20).

The reduction in formability was attributed to a strong anisotropic behavior caused by the dendritic based microstructure of the deposited sheet. Authors also concluded that the growth of stable necks within the primary arms of the dendrites gave rise to striations that are visible on the surfaces of the parts (refer to Fig. 20a).

4.3.3.4. Spinning. Shirizly and Olev (2019) presented the first integration of additive manufacturing with spinning. The authors utilized metal deposition by GMA-DED to fabricate tubular preforms that were subsequently machined and plastically deformed by both forward and backward external tube spinning operations to reduce wall thickness and produce longer tubes (Fig. 21). Tests carried out in low carbon and stainless steels allowed concluding that the deposited preforms can successfully be used to produce tubes with mechanical properties similar or even better than those of parts produced from wrought (fully dense) preforms.

4.3.4. Integration with joining by forming processes

Recent years saw a growing interest in the application of joining by forming processes for the assembly of structural components. Elimination of the metallurgical problems caused by the heating-cooling cycles and by the incidence of hard and brittle intermetallic compounds with the aptitude to join dissimilar materials are some of the reasons that justify the interest in replacing conventional welding, fastening and adhesive bonding by joining by forming. Hybridization of additive manufacturing with joining by forming processes further extends this interest by adding flexibility, environmental compliance and adequacy for producing small, medium and large batches of joints.

Ucsnik et al. (2011) where the first to combine additive manufacturing with joining by forming to produce double-lap shear joints made of an inner stainless steel core and two outer carbon fiber reinforced plastic (CFRP) layers. GMA-DED was utilized to deposit pins with different shapes (cylinder, ball head and spike) on the inner stainless steel sheets, so that they would fully penetrate the upper and lower CFRP sheets and create a mechanical interlocking after pressing the three sheets together by upsetting.

Silva et al. (2019) also utilized additive manufacturing and joining by forming to 'create mortise-and-tenon' joints between two overlapped metal-metal and metal-polymer sheets. They installed a GMA-DED system in a robot to deposit rectangular cross section pins (tenons) on top of aluminum sheets while mortises (rectangular cavities) were cut out on the adjacent aluminum or polycarbonate sheets. Subsequent upset compression of the free length of the tenons ensured the mechanical

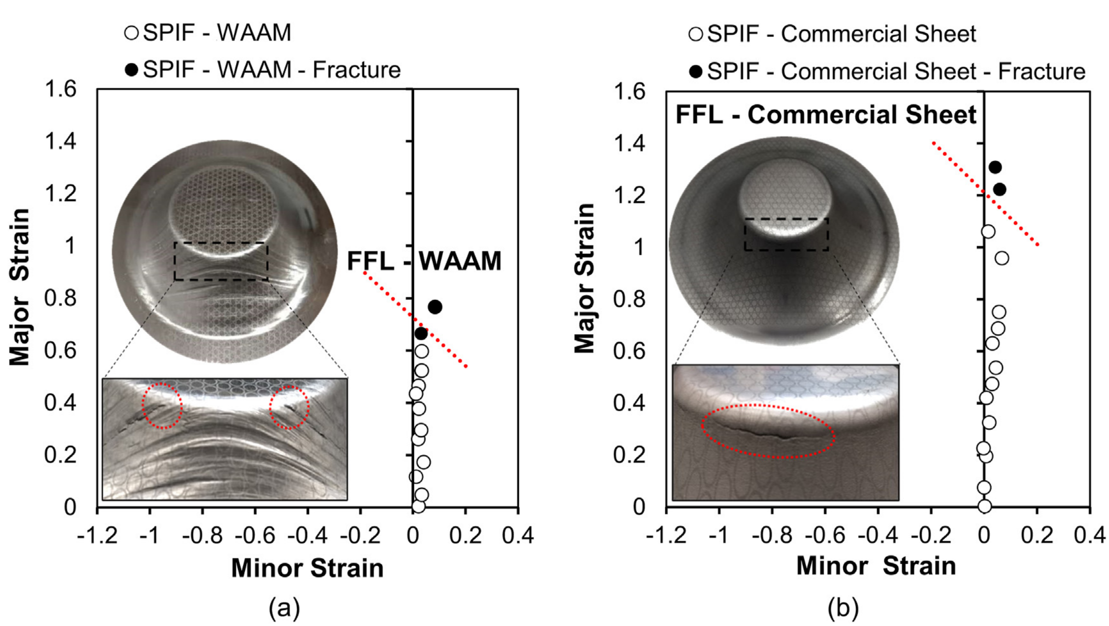

Fig. 20. Major and minor strains along the meridional direction in single point incremental forming of truncated conical shapes made from (a) deposited and (b) commercial AISI 316 L sheets. The solid markers correspond to fracture (adapted from Pragana et al. (2020)).

locking between the two sheets to be joined (Fig. 22).

Destructive tensile (pull-out) tests on the mortise-and-tenon joints shown in Fig. 22 revealed two different detachment modes. In case of monolithic aluminum joints, the sheets were separated by shearing off the tenon whereas in case of aluminum-polycarbonate joints separation was accomplished by plastic deformation of the polycarbonate mortise while the tenon is drawn by means of the applied pull-out loading.

In a subsequent work (Baptista et al., 2020) applied the above mentioned hybrid additive manufacturing process for joining hollow section aluminum profiles to composite sheets in order to demonstrate the feasibility of the process to assemble other than overlapped sheets and to illustrate its potential for the construction of lightweight structures (Fig. 23).

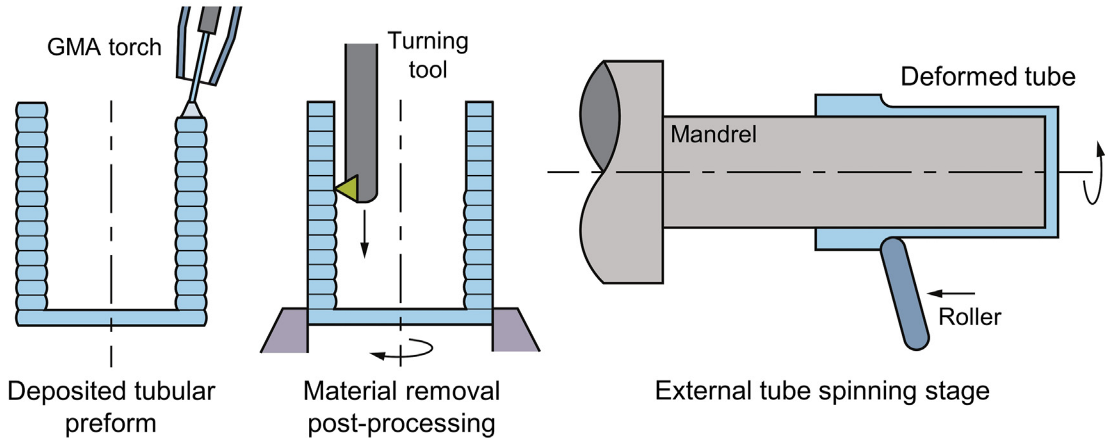

Fig. 21. Schematic representation of the integration of metal additive manufacturing with external tube spinning.

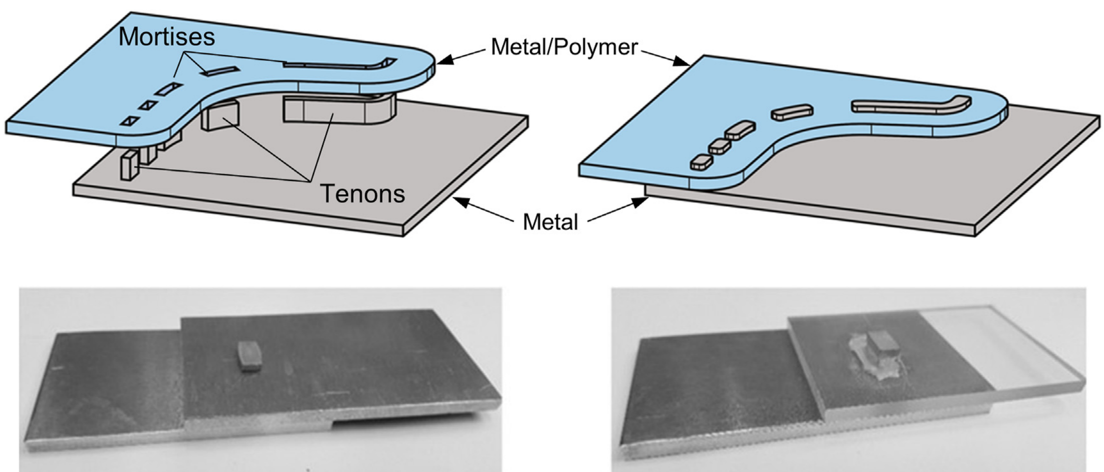

Fig. 22. Schematic representation of the hybrid additive manufacturing process to produce mortise-and-tenon joints between sheets of similar and dissimilar materials partially placed over one another. The photographs show a monolithic aluminum joint (left) and an aluminum-polycarbonate joint (right) (adapted from Silva et al., 2019).

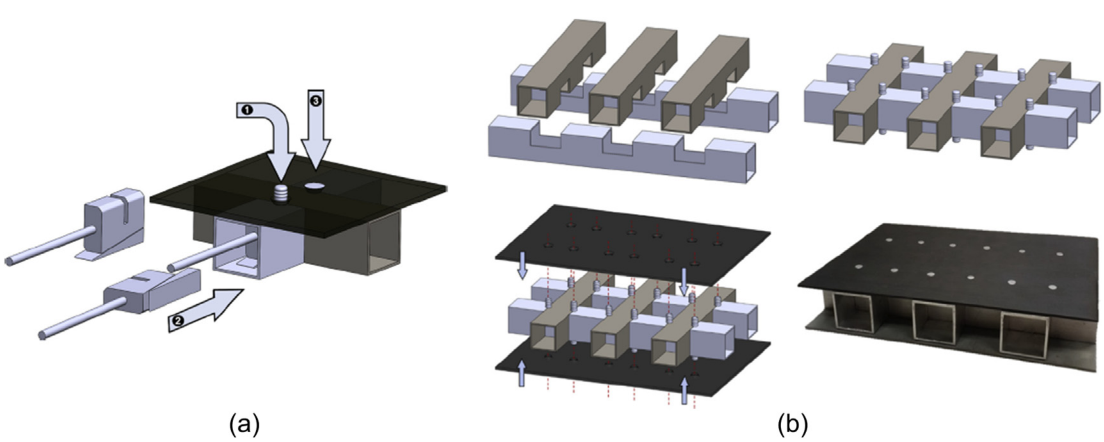

Fig. 23. (a) Procedure to obtain a mortise-and-tenon cross joint between two square hollow section profiles and a composite sheet and (b) application of the procedure to construct lightweight structural panels with photograph of a real part (adapted from Baptista et al., 2020).

5. Conclusions

This paper was intended to take the readers in a journey that started with the history and working principles of additive manufacturing and ended with an overview on the hybrid additive manufacturing processes that have been developed in the last decade.

The definition of hybrid manufacturing was reviewed to enlarge its applicability to the utilization of materials other than primarily processed raw materials in the form of ingots, plates, sheets, rods, tubes, profiles, powders, and pellets. The new proposed extension opens the way to the emergent novel hybrid manufacturing routes built upon the controlled application of process mechanisms on additively deposited materials and the controlled application of additive manufacturing on primarily processed raw materials previously subjected to traditional manufacturing processes.

Special emphasis was placed on the hybridization of additive manufacturing with forming processes, namely bulk and sheet forming processes as well as to processes for improving the mechanical properties of the additive deposited materials, and to joining by forming processes.

All in all, the paper shows that hybridization of metal additive manufacturing with traditional manufacturing processes fulfils the important two-fold objective of (i) increasing the applicability domain and overcoming the limitations of additive manufacturing related to low productivity, metallurgical defects, rough surface quality and lack of dimensional precision and (ii) adding flexibility and fostering new applications with traditional manufacturing processes/routes.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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