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REVIEW

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Powder-bed additive manufacturing for aerospace application: Techniques, metallic and metal/ceramic composite materials and trends

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Abstract. The current paper is devoted to classification of powder-bed additive manufacturing (PB-AM) techniques and description of specific features, advantages and limitation of different PB-AM techniques in aerospace applications. The common principle of "powder-bed" means that the used feedstock material is a powder, which forms "bed-like" platform of homogeneous layer that is fused according to cross-section of the manufactured object. After that, a new powder layer is distributed with the same thickness and the "printing" process continues. This approach is used in selective laser sintering/melting process, electron beam melting, and binder jetting printing. Additionally, relevant issues related to powder raw materials (metals, ceramics, multi-material composites, etc.) and their impact on the properties of as-manufactured components are discussed. Special attention is paid to discussion on additive manufacturing (AM) of aerospace critical parts made of Titanium alloys, Nickel-based superalloys, metal matrix composites (MMCs), ceramic matrix composites (CMCs) and high entropy alloys. Additional discussion is related to the quality control of the PB-AM materials, and to the prospects of new approaches in material development for PB-AM aiming at aerospace applications.

Keywords: additive manufacturing / aerospace materials / powder-bed / high entropy alloys / titanium alloys / superalloys

1 Introduction

The powder-bed additive manufacturing (PB-AM) unifies several 3D-printing powder-based techniques: selective laser sintering/melting (SLS/SLM), electron beam melting (EBM) and binder jetting printing (BJP). PB-AM is widely used in critical applications like biomedical implants [1,2], automotive [3], and aerospace [3,4].

PB-AM with the high power beams is used for different group of materials: from light metals like Aluminum [5,6] and Titanium alloys [7–10], to steels [5,11–13], and even refractory Tungsten [14], Tantalum [15], Inconel [16–21], high entropy alloys (HEAs) [22–29] and bulk metallic glass (BMG) materials [30–31]. In special literature, the term "additive manufacturing", in relation to both metallic materials and polymers, is more common than 3D-printing commonly used in the news popular literature. Out of many AM methods, only few can be regarded as "printing" and "additive" stresses the difference with more common "subtractive" manufacturing methods. Freedom of shapes achievable in a single manufacturing process, energy and material savings and faster design-to-production times are among most prominent advantages of all AM methods including its powder-bed versions. These advantages provide the "buy-to-fly ratio" for PB-AM components close to 1:1.

The current review aims to present the state-of-the-art in materials used in PB-AM specifically for aerospace application.

2 Powder-bed additive manufacturing

As stressed by the name, PB-AM uses powders as a precursor material. In beam-based PB-AM machines, thin layers of powder are deposited and leveled by dedicated mechanical systems and selectively melted by high power

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beam (laser or electron one) in the places where solid metal should occur. This process is consecutively repeated forming desired components layer-by-layer. The process is carried out either in inert atmosphere (SLM) or under vacuum (EBM) to prevent material and component oxidation [32–36]. Unlike other traditional ways of metal processing, only a small amount of material is melting around the beam position resulting in very high heating and cooling rates. These unique processing conditions define the microstructure of the material resulting from PB-AM, and in few cases, materials can acquire unique properties (e.g. HEA and BMG).

In general, laser-based machines dominate the PB-AM equipment market in numbers and variations. One of the largest competitive advantages of the laser-based PB-AM systems over EBM is in significant number of industrially available metallic materials. So far, a single EBM machine manufacturer, ARCAM EBM [32] (now part of the GE) is holding majority of the key patents preventing other equipment manufacturers to provide competitive alternatives. Unfortunately, so far ARCAM EBM supports only few materials for industrial manufacturing (Ti64, Ti grade 2, CoCr ASTM F75 and Inconel 718).

PB-AM systems are commonly using pre-alloyed powders with the powder grains close to spherical shape allowing good definition of deployed powder layers. Laser-based PB-AM systems are commonly using rather fine precursor powders with the grain size starting from few microns, but most common are the powders the grains up to 60–80 micron. Electron beam melting PB-AM uses coarser powders with the grain size distributions commonly between 75 and 150 micron. Correspondingly, laser-based PB-AM machines use thinner powder-bed layers as compared to EBM and allow for some better spatial resolution in manufactured components (strongly defined by the powder grain size and layer thickness). Correspondingly, EBM with some thicker layers and higher achievable energy in the beam can provide higher production rates. Thus commonly for the manufacturing of smaller components with finer structure details the choice is with laser-based methods, and with larger components and higher throughput- with EBM.

Traditionally, PB-AM methods are using gas- or plasma atomized powders [7,37] made from pre-alloyed material. But in cases when non-equilibrium material microstructure is desirable (like with BMG, HEA and some other materials), blends of elemental powders can be used [28,30,31,38–40].

A common feature of PB-AM techniques is the need to use special supports to keep the part under construction from thermal deformations. Because newly manufactured hot material coexists with the loose or slightly semi-sintered powder having relatively low heat conductivity possible shape distortions can occur. Thus, manufacturing is always initiated from so-called start platform (commonly a relatively thick stainless steel plate) providing a good heat sink. Also, thin support structures (scaffolds) are used under all overhanging component elements. In many cases, especially when used materials are easily welding with stainless steel, support structures are also placed between the component and the start plate. These supports are removed after component is taken out from the machine after manufacturing.

Generation and placement of supports is essential part of the design file preparation for AM. Corresponding software for automatic support generation is available from the machine manufacturers and independent vendors. But proper support placement depends on the designer skills balancing minimization of material waste (minimum supports, as they are removed and cannot be returned into the process as unused powder) and component shape integrity (increasing support number preventing first layer delamination and heat deformations).

In the majority of cases, components produced in PB-AM will need certain post-processing. Here three aspects related to as-manufactured state of the PB-AM components should be kept in mind: component surface roughness; different thermal history of the different parts of the component; possible residual stress in the material and presence of the supports. Because molten metal in PB-AM is directly neighboring loose or slightly sintered powder, component outer surfaces will have certain roughness, with average values commonly determined by the dimensions of the used powder grains, partially fused with the outer surfaces [41,42].

The components manufactured using PB-AM systems keeping the working area at highly elevated temperatures commonly have rather small residual stress. Such situation is true with EBM and with only some of the laser-based systems. But in most laser-based systems without additional preheating, where cooling of material behind the beam spot is happening very fast down to relatively low temperatures of the component, residual stress may present a serious problem. Thus post-processing (most commonly hot isostatic pressing) is performed [43]. Also, in all cases when component manufacturing time is significant, lower (first) and upper (last) material layers are having very different thermal history and thus may result in a different microstructure. Thus, in all cases when the microstructure of as manufactured parts is undesirable because of non-stationary heating-cooling process, or non-uniform due to the different thermal history, additional post-processing is advised.

Removing of the support structures is so far not well automated, and in many cases demands manual operations. Also, when removed, supports commonly leave relatively rough areas on the component surfaces. Excess surface roughness and remaining support structures can be treated using different chemical and electrochemical methods [44,45]. But most complicated is removal of the support structures placed in the inner channels inside the components, but industrial methods for removal of the support structures in "hard to get" spaces are start to emerge [46].

It should be noted that, despite wide commercialization of PB-AM equipment, industrial application of such methods demands special attention. Firstly, all elements of the manufacturing chain (materials, equipment, metrology, quality control, safety, life cycle analysis etc.) differ from what is well established with other methods of manufacturing of metallic components. AM systems are complex and include equipment for: sifting and mixing powders; loading and unloading the machine; post-processing; filtration and cooling; powder storage; generating and feeding inert gases; etc.
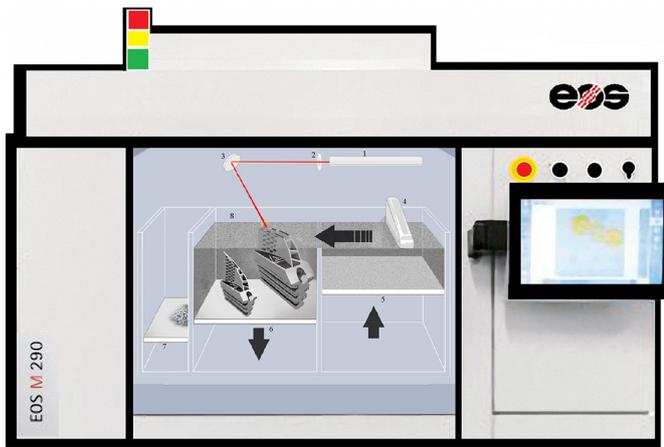
Fig. 1. Selective maser melting process: 1: laser; 2: lenses; 3: x-y-scanning-mirror; 4: rake; 5: powder supply table; 6: build table; 7: table for rest powder; 8: powder-bed.

Because running such systems demands certain knowledge of operators, and especially because of the specifics of "designing for AM", many businesses are opting to design components together with the specialists and order component manufacturing from the trusted companies specializing in AM manufacturing.

Non-beam-based PB-AM technologies are also developing becoming especially competitive in the case of manufacturing non-metallic materials (ceramic, ceramic-based, composite). Binder jetting printing (BJP) is a good example of such PB-AM industrially applied technique.

2.1 Selective laser melting

SLM was the first powder-bed-based technique enabling to "print" metallic alloys. Nowadays, there are multiple producers of SLM machines that use different terminology (trade names) for almost the same SLM process. For example, EOS calls there process direct metal laser sintering (DMLS); Renishaw – metal powder-bed fusion (MPBF); Concept Laser – LaserCUSING®; etc. [35].

Figure 1 schematically illustrates the SLM-process, where powder layer is deposited using so-called rake system "brushing the powder in" layer-after-layer with the most common layer thickness for light metals of 30–60 microns. Some of the systems use inert gas atmosphere (nitrogen or argon), some other work in mild vacuum. Ytterbium fiber laser systems usually applied to sinter metallic alloy powder in modern SLM systems.

In general, in manufacturing of complex parts, laser power control is extremely desirable, but it is not easy to implement. The higher is the laser power, the faster is melting and shorter lead time. Today, some equipment manufacturers commercialize the system with multiple lasers allowing speeding up manufacturing process. But in all PB-AM including both laser and e-beam- based ones layer processing time cannot be reduced indefinitely, certain amount of beam power delivered per surface area is always needed to avoid excessive porosity and lack of fusion defects in the resulting component. Increasing beam power also increases the dimensions of the melt pool thus reducing the ability to generate parts with very small geometric features. Thus in the cases demanding highest spatial resolution in the component shape, the beam energy should be lowered, inevitably resulting in longer component processing times [35].

Thus SLM process is beneficial for manufacturing of components with small accurate features, with the elements less than 300 microns; internal channels; lattices and similar lightweight structures; honeycomb structures and complex heat exchanger structures [47]. The physical and mechanical properties of SLM-manufactured parts could be controlled and optimized by process parameters development [48–50] and also by thermal post-processing.

2.2 Electron beam melting

Melting of metallic materials by electron beam was quite common for electron beam welding (EBW), well-known process for Titanium alloys, steels and some other metals. But, merging high power of the beam with its precision control resulted in a new manufacturing method: electron beam melting (EBM, or SEBM – selective electron beam melting). Corresponding beam energy up to tens of kilowatts in the beam and very small beam reflection from metallic powders give EBM certain advantages over laser-based PB-AM methods. Process is carried out in high vacuum (down to 10^{-5} bar) with powder layer semi-sintering and preheating resulting in elevated process temperatures (about half of the melting temperatures of used material) (see Fig. 2). Layer preheating before melting in vacuum provides additional powder surface degasification and desorption, and prevents powder and component oxidation. Higher available beam energies allow using powders with the grain size distribution of about 75–150 micron, and corresponding layer thicknesses of 50 to 200 micron [51,52]. This can provide faster layer processing times as compared to the ones common for laser-based PB-AM machines, but leads to correspondingly lower spatial resolution in component shape details, and higher component surface roughness. Preheating during whole manufacturing process leads to significantly lower internal stresses in as-manufactured components, and in some cases much better mechanical properties as compared for with traditionally manufactured alloys [32]. High power of the beam and vacuum conditions are also quite favorable for manufacturing materials with the microstructure preserving metastable states (HEA, BMG).

Semi-sintering of the powder is a feature significantly differing EBM from the laser-based PB-AM methods. This stage is necessary due to the fact that high power electron beam hitting the loose powder causes its charging. As a result, powder rises up in vacuum chamber forming a cloud (event known as "smoke"), which is stopping the process and can damage the machine. Thus, pre-sintering and preheating of the deposited loose powder layer is carried out with successively increasing beam current. Semi-sintering of the powder has both positive and negative consequences. Comparing to laser-based PB-AM, inside
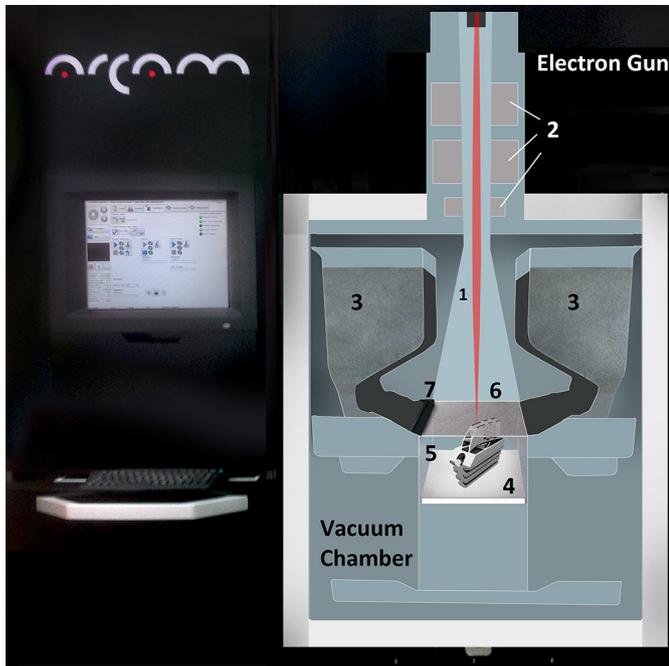
Fig. 2. Electron beam melting process: 1: electron beam; 2: electron beam control; 3: powder containers; 4: build platform; 5: build tank; 6: working area; 7: rake.

Fig. 3. Binder jetting printing process: 1: binder jetting head; 2: rake and powder delivery system; 3: working area; 4: build tank; 5: build platform.

layers. A wide range of polymer, composite, metallic, and ceramic material processing was demonstrated, but only a few of them are commercially available. BJP production technology uses various granular/powder materials (sand, ceramic powders, metallic alloys). The printing stage requires a low heating (200 °C). At the sintering step, high-quality and uniform heating is normally achieved. This factor leads to significant reduction in residual stresses compared with the beam-based methods of PB-AM. [17,55]. As is reported in the recent literature, use of BJP technology permitted to many researchers successful printing of different types of alloys, including superalloys and ceramic matrix composites (CMCs) using BJP process [18,19,56–59].

3 Materials

Aerospace applications demand materials with certain critical properties, like high strength to weight ratio, high temperature operation. Aerospace application that demands cutting edge technologies is becoming one of the primary beneficiaries of AM. In particular, PB-AM already allows for manufacturing components with complex shapes from light metals with high mechanical strength like Titanium alloys and refractory materials like Ni-based superalloys provide quite promising manufacturing pathways. Possibility of extremely fast localized melting and cooling in PB-AM also allows for manufacturing multiple new material families with unique properties preserving a non-equilibrium states in their microstructure. Among such materials one should specifically mention high entropy and amorphous alloys. For example, amorphous or glassy alloys commonly called bulk metallic glasses (BMGs) are promising a breakthrough in the applications capable of utilizing their unprecedented resilience.

3.1 Titanium alloys

Titanium alloys provide a unique combination of physical and mechanical properties like small weight, high strength (high "strength to weight ratio"), good corrosion and fatigue resistance. Unlike carbon-based composites [60],

semi-sintered powder it is easier to stack multiple separate components in the build volume increasing component yield "per build", and makes lower demands to the number of support structures. On the other hand, a powder from the crevices, from inside the cooling channels and lattice structures can be simply shaken out. And, removing powder from such structures after EBM is significantly more complicated.

2.3 Binder jetting printing

The high temperature PB-AM allowed produce metallic parts, as well as MMCs which are, as known, contain some amount of ceramic phase dispersed in metallic matrix [36,53]. Manufacturing of high quality ceramic parts by this technique is still challenging and certain efforts are needed for its wide industrial acceptance. Thus another approach, at which melting does not occur at the first manufacturing stage, is used for PB-AM of ceramic parts. This PB-AM technique is called binder jetting printing (BJP). It uses particles bonding (binding) occurring throughout layer-by-layer building of a "green" (non-dense) part from a raw ceramic powder (see Fig. 3). Then, the manufactured "green" is subjected to post-processing (binder removal at high temperature and material's sintering) to obtain the final dense part.

BJP is a process, in which a binder is deposited onto a powder-bed to form part cross sections (see Fig. 3) [54]. This concept can be contrasted with traditional metal PB-AM, at which high intensity beam (laser or electron one) melts powder particles to form a consecutive solid material
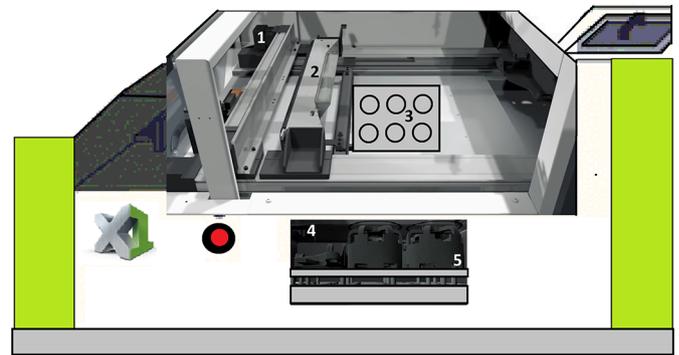
aluminum [6] and magnesium– the Ti alloys can withstand high serving temperatures (for example aluminum usually serves up to 200 °C). Excellent corrosion resistance is another factor making Ti alloys quite useful for aerospace applications.

One of the most popular Ti alloys is Ti–6Al–4V, finding its place both in aerospace [61] and medical applications [1,2]. Up to now it is the most popular material used in AM. The weight percentage of titanium in large commercial aircrafts varies between ~7% in the airframe and ~36% in the gas turbine engines. Titanium is used as fatigue crack growth "stopper" in aircraft fuselage made from aluminum and also for hydraulic system pipes. Primary components of aircraft landing gear are also manufactured from forged Ti alloys. Also other structural parts like the frames of cockpit windows, kitchen and toilet parts, various fixation elements and brackets are manufactured from pure Titanium or Titanium alloys [61].

Another important property is the compatibility between Ti and C-fiber reinforced polymer (CFRP), the matching between their thermal expansion coefficient and the galvanic corrosion resistance between them make the Ti alloys very attractive for composite structures [61,62].

Though applications of Ti alloys in civil aviation are quite significant, these alloys are even more widely used in military aircrafts, helicopters and space applications due to the need of high performance and unique properties, especially weight reduction.

Post treatment is sometimes required for structural parts in order to enhance their mechanical properties. Heat treatment, coatings and surface modifications are being applied to titanium structures, according to their specific use. The most used post-processing procedure for titanium parts is hot isostatic pressing (HIP), which decreases the residual porosity and improves material microstructure resulting in improved fatigue stability [43].

Beneficial properties of Titanium alloys for aerospace to large extent defined these alloys to be one of the primary targets for PB-AM material development. In PB-AM of Titanium alloys the phase formation and mechanical properties can be controlled by process parameters optimization [7,8,10,63]. Additive manufacturing of Ti-alloys has significant advantages comparing to traditional manufacturing, because of low castability and challenging machining of these alloys.

In some of the aerospace applications, like turbine blades, the resistance to fatigue is quite critical, thus improvement of as-manufactured by PB-AM component surfaces is necessary (mostly the reduction of roughness). As mentioned above, PB-AM results in a poor (rough) surfaces, so different post processing technologies are available and are continuously developed. Most of the surface treatment methods are multi-step processes that include the use of abrasive media (physical treatment) and chemical and electrochemical polishing. These methods are also combined with traditional machining, whenever needed.

3.2 Ni-based superalloys

In recent years, research interest in production Ni-based alloys in significantly increased, especially targeting the applications for the applications demanding high temperature low fatigue, common in aviation and aerospace industries [64–69]. In general, the term "superalloy" refers to metals that have been developed to withstand high temperatures without deforming or corroding. These alloys often combine such important parameters as outstanding yield and fatigue strength, surface stability and resistance to creep and thermal creep deformation [70–73]. Nickel-based alloys are most commonly used in various applications related to the aviation and aerospace industries, though certain applications in chemical industry demanding high corrosion stability in aggressive media at high temperatures can be found. The most recommended and currently known Ni-based superalloys used in mechanical engineering are so-called Inconel 718 and Inconel 625.

Among beneficial properties of Inconel 718 (Ni–Cr-based alloy) are corrosion resistance; fatigue, creep, and rupture strength; high working temperature (up to 980 °C); with tensile strength up to 1400 MPa and 21% elongation at room temperature [18,74]. Hardening of the alloy is achieved due to the slow release of the intermetallic compounds of Ni with Ti and Nb [17,21,75]. Inconel's weldability and post-weld behavior (resistance to cracking) are also superior [76]. Unique combination of mechanical and physical properties of this Ni-based alloy resulted in a wide range of applications, including aerospace. Typical examples of components produced from Inconel 718 are components for liquid fuel rockets, fasteners, casings, instrumentation parts, and for aircraft and land-based gas turbine engines [73,77].

Inconel 625, another Ni–Cr-based alloy, is used for its high strength, excellent manufacturability (including joining), and outstanding corrosion resistance. Service temperatures range from cryogenic to 982 °C [74,78,79]. Strength of Inconel 625 is resulting from the stiffening effect of Mo and Nb on its Ni–Cr-matrix; thus precipitation-hardening treatment is not required. This combination of elements also is responsible for superior resistance to a wide range of corrosion mechanisms and ability to work in strongly aggressive environment, as well as to the resistance to high-temperature oxidation and carburization. High tensile, creep, and rupture strength, outstanding fatigue and thermal-fatigue strength; oxidation resistance; and excellent weldability and brazeability are the properties that make Inconel 625 advantageous for the aerospace applications. It is being used in such applications as aircraft ducting systems, engine exhaust systems, thrust-reverser systems, turbine shroud rings, and heat-exchanger tubing in environmental control systems [20,79,80].

3.3 Ceramic and metal matrix composites

CMCs and MMCs are a subgroup of composite materials, containing at least two phases with the dominating material being ceramic or metal correspondingly. As it is the common case with other composite materials, CMCs and MMCs show certain properties exceeding the ones of each constituent separately. Sometimes, their reinforcing phase consists of ceramic fibers embedded in a ceramic matrix [81]. In the last decade, intensive research was focused on the development of composite structures based

on non-oxide compounds such as carbon, silicon carbide (SiC) and nitride (Si_3N_4), tungsten carbide (WC) etc. These compounds can be either a matrix or a reinforcing filler in the form of continuous or discrete fibers, whiskers, (combinations C/C, C/SiC, SiC/SiC) or micro- and nano-particles. Such materials are often characterized by high strength, heat resistance, low density, and abrasion stability. These properties allow them to be used in aviation and space technology as high-temperature structural materials, for the elements of gas turbines, diesel engines, heat-exchangers, and in tribo-technology [82–86]. Composite materials of the type C/SiC and SiC/SiC are distinguished by low specific gravity, wear resistance, the possibility of the formation of these products of complex shape, in reducing conditions of operation, these composites retain high mechanical properties up to a temperature of 2000 °C [87]. The most promising material at present is SiC and SiC-based materials, which allow to obtain the specified combination of properties: high specific strength and rigidity; heat resistance; wear resistance; high thermal conductivity and heat-shielding properties; radiation strength [88]; etc.; thermal conductivity of 180–200 W/(m·K) (as in Al), in single crystals up to 470 W/(m·K); working temperature – more than 1350 °C (as in heat-resistant steels); melting/decomposing point is 2830 °C; resistance in the oxidizing and reducing environment is higher than that of Ti [89]. PB-AM technologies demonstrate significant potential in manufacturing of composite materials both from the blended powders and pre-agglomerated powders where each grain already contains multiple materials sintered together [28,38,39,90].

3.4 High entropy alloys

HEA belong to relatively novel class of metallic materials composed by at least five constituents in nearly equimolar concentrations with a thermodynamic preference to form one or more solid solutions instead of intermetallic compounds. The basic research in this novel topics of materials engineering and technology have been done by Yeh et al. [91], Wang et al. [92] and Zhang et al. [93]. Since configurational entropy of elements' mixing in disordered solid solution mixing is high (this is the reason for the term "high entropy alloys"), HEA's stability increases with temperature [91,92]. Due to this tendency, no undesirable intermetallics-induced embrittlement or precipitation over-hardening are expected in these materials. Solid solution strengthening obtained through complex mutual alloying, achieved through HEA synthesis, is expected to result in unique high mechanical properties, especially at elevated and high temperatures, namely: high temperature strength combined with creep resistance and high temperature fatigue resistance [93].

Presently, two main groups of HEAs can be mentioned: HEAs with face-center cubic (FCC) and HEAs with body-centered cubic (BCC) crystal structure. To the first group belong alloys composed mainly of transition metals, while the second one contains mainly refractory metals-based alloys. The basic researches in BCC refractory metals-based HEAs have been done by the group Senkov et al.

[94–100]. Taking into account the continuously growing demand in more temperature resistant materials for high temperature applications in aerospace industry [93–102], for example, in critical high-temperature parts with superior properties, like turbine blades [4], it becomes clear that refractory metals-based BCC HEAs are good candidates for these important applications [93–102]. Preliminary researches available in a scientific literature report on a principal possibility to synthesize BCC HEAs with can successfully serve as turbine blades at significantly higher temperatures that those available now through use of Ni-based superalloys [93–102].

The current processing of synthesizing HEAs is a vacuum arc melting [103–107]. Throughout applying this method, a vacuum atmosphere is used while heating the alloying materials up to a temperature higher permitting their complete melting. Then, liquid state mixing and mutual dissolution occurs. After completion of this process, the as-obtained homogeneous liquid is solidified and then the obtained solid is subjected to heat treatment. Usually, the last one is necessary for chemical and microstructural homogenization, which is critical for formation of the desired mechanical properties. The difference in melting points and vapor pressures of the alloying materials at high temperatures may be a quite problematic point of the mentioned process, especially in refractory metals bases HEAs, at which the melting points of the alloying materials are high and the castability of such complex liquid blend is insufficient to obtain a homogeneous material through the following solidifying. Furthermore, oxidation resistance of refractory metals is usually insufficient to obtain a product completely pure from oxidation, even under operating vacuum typical for high-temperature arc-melting furnaces. Taking into account the problematic aspects of the arc-melting under vacuum, it can be concluded that more appropriate HEA production route should be used for synthesizing refractory metals-based BCC HEAs.

One of the potential novel routes, which can be proposed for HEAs production, is PB-AM [22–29,32,39,51,90,108–111]. The process permits a wide freedom to obtain almost all complicated part's geometry as desired. Obviously that this route could be used even for the parts made of the HEAs containing elements with low oxidation resistance and poor castability [34].

Traditional raw materials for PB-AM are pre-alloyed powders. Since the mutual alloying of the constituent elements composing such powders has been fulfilled throughout their production, their use is a convenient way to obtain homogeneous microstructures of as-printed products. On the other hand, if some unique raw material composition is required or some compositional fine-tuning of the product is required, the appropriate powders may unavailable or extremely expensive despite the availability of various methods for their manufacturing. Presently, insufficient availability of the pre-alloyed powders for new perspective materials is one of the constraints significantly slowing the progress of PB-AM, in general, and PB-AM of refractory based HEAs, in particular. Though the growing interest in the development of new materials for PB-AM is continuously increasing, today's state of the art regarding

the trials for in situ alloying in PB-AM aiming at HEAs remains very restricted. Only few reported researches on this matter can be mentioned [22–29,32,39,51,90,108–111].

3.5 Bulk metallic glass

BMGs (amorphous metal, metallic glass) can be regarded as "one step further" compared to HEA, as these are metallic materials "without crystalline lattice". If in HEAs the main factor affecting microstructure formation is high configurational entropy of non-ordered solid solutions [91–93], then BMGs formation is dictated by a crystallization delay caused by a suppressed diffusion resulted from kinetic factors like cooling rate and low mutual diffusivity of alloy's constituents [112–116]. It means that within the BMG's microstructure there is no long-range order [114,116]. Invented as more or less "scientific curiosity", these materials appeared to have a number of unique properties such as top hardness, strong abrasion and corrosion resistance even in the harshest of environments, superb fatigue properties and exceptional resilience unbeatable by any other known material [117]. Materials for modern iron-based BMG compositions manufacturing are not more expensive than the ones for high grade steels [30]. Ability of beam-based PB-AM of extremely fast highly localized melting and fast cooling make it extremely promising for BMG manufacturing [30,31]. Unfortunately relatively low glass transition point (heating above it and slowly cooling BMG returns it to crystalline state) commonly being within 450 to 580 °C strongly limits their application. In view of this most promising applications for aerospace and automotive industry are abrasive and corrosion resistive coatings and spring-like structures. And though BMG coatings can be applied using plasma spray technology, new modalities available from AM (see below on the composition-graded materials) seem to be quite promising for the future. Outstanding resilience together with exceptional fatigue stability promise to make BMGs a prime choice material for spring manufacturing. Simulations from material properties indicate that coil and leaf springs having same footprint and basic outline, and the same spring constant would be 5 to 10 times lighter if made in BMG, and will serve significantly longer as compared to the ones made from other materials. Thus design of new BMG materials and development of AM processes for their manufacturing is dramatically gaining pace.

4 New modalities available with PB-AM

Specifics of the PB-AM also allows for additional advantages resulting from the modalities available with AM but not with other technologies. Rather well known for PB-AM capacity for manufacturing thin-walled, honeycomb, cellular and other lightweight structures together with other sections of a component in the same manufacturing process open a whole lane of opportunities for the automotive and aerospace applications. Fast localized melting and cooling intrinsic to PB-AM was already mentioned above related to the manufacturing of HEA and BMGs. Other modalities like the ability of manufacturing so-called composition- and functionally-graded materials, and microstructure (and thus- property) steering in 3D also available with PB-AM are among additional unique options becoming available.

4.1 Lightweight structures

One of the common weight reduction possibilities beyond the choice of lightweight alloy is incorporating openwork sections into the components. Due to the shape flexibility of PB-AM, lightweight sections can be easily made together with the solid sections of a component in a single manufacturing process. Typical examples of such components are thin-walled ones (like honeycomb structures [118]) as well as lattices (cellular) structures of different design [119,120]. Another feature significantly differing PB-AM manufacturing is that there is no need to make lightweight structures fully repetitive and symmetric. This opens the possibility to vary the properties of the lightweight structures (apparent density and unit cell dimensions) by design, stepwise or gradually [121]. More complex designs, with the anisotropic unite cell lattices providing anisotropy of the structure mechanical properties, are also possible. Though manufacturing of such lightweight components is entirely possible, their design is still a complex undertaking due to the lack of powerful enough software tools for automated generation of, for example, high complexity lattice structures.

4.2 Compositionally- and functionally-graded materials

Another unique possibility is provided by the PB-AM systems capable of advanced powder feeding and localized beam energy deposition variation. For example, changing the composition of the powder in consecutive layers (changing materials, changing blending ratio of materials) already allows for manufacturing compositionally- and functionally- graded materials [39,121]. So far, the early attempts are made with only slight modifications of the commercial PB-AM systems, which limit them to only planar structure manufacturing. But engineering community is already looking for the powder delivery solutions allowing for the material changes within a single layer. One of the definite advantages of the compositionally- graded materials, where the mixing ratios of two different powdered materials is gradually changes layer from layer is in the enhanced stability of such structure to the thermal and mechanical load cycling. In the typical example of the hard coating on the softer metallic material thin boundary layer between two concentrates high stress during loading or changing temperature conditions. With gradual change in the material composition levels of such stress is considerably lower.

Because the microstructure of the PB-AM manufactured materials depends on the thermal conditions during melting-solidification process it is possible to vary the material microstructure and thus material properties locally, within essentially a single layer, varying the energy deposited by the beam [39]. It was also shown that such beam energy deposition steering combined with feeding blend of two powders allows to locally change the

composition of the component going from composite to mixed alloy [28,39]. This allows the structures with hard abrasive resistant outer surfaces and reinforcement elements inside surrounded by amore ductile "core".

This expanded methodology can be already called true 4D-printing, where flexibility comes in three of spatial dimensions, and material composition as a fourth dimension. Such space- and material flexibility on one manufacturing process will definitely find valuable application in different technological areas including automotive and aerospace industry.

5 Future trends and challenges

Taking into account the growing demand in novel high-performance materials with unique combination of mechanical, physical and chemical properties, certain main future trends in PB-AM can be envisaged.

Firstly, the industrial acceptance of PB-AM will continue to grow across the industries, including few sectors most benefiting of its development – aerospace, automotive and biomedical ones. The growth of the PB-AM applications using materials already traditional for aerospace and automotive industry like Ti-based, Fe-based, Al-based alloys will continue mainly around the possibilities of manufacturing components with complex shapes, incorporated lightweight structures, cooling channels. Here the benefits could be expected primarily from weight and cost savings per manufactured component. Additional benefit could be expected in reducing the spare part handling costs, as in many cases storing large numbers of different items can be substituted by manufacturing parts on demand from saved computer files.

Secondly, the trend towards using unique capacity of PB-AM methods of manufacturing components from materials with highly attractive properties will continue to grow. This trend is already well pronounced, and it starts with the PB-AM manufacturing with materials that are hard or impossible to process using other manufacturing methods, either due to the demanded component shape complexity, or due to the resulting material properties. This trend will see further development of PB-AM manufacturing and of Ni-superalloys and their wider acceptance in automotive and aerospace applications, as well as introduction of industrial processes for HEA and BMG.

Thirdly, the trend of incorporating PB-AM manufacturing into unified automated and robotic processing lines together with the post-machining and post-processing will continue. Many of such systems are already in development, and were already shown to provide better integration of the PB-AM manufactured components into existing industrial process lines.

One of the developing trends promising large benefits for aerospace and automotive industries is PB-AM manufacturing of components from materials with controlled properties throughout their volume by precisely controlling the material composition and microstructure, adding 4th dimension to 3D-printing. Possibilities of

powder blends with varying composition in BJP and beam-based PB-AM, steering the microstructure of the components inside the component by adjusting the beam energy deposition selectively in each layer with beam-based technologies were already successfully demonstrated.

There are certain challenges preventing PB-AM to gain wider acceptance in the industrial manufacturing. Few of them are related to the integration of PB-AM into the existing, well-established technological chains. These challenges are ranging from differencing in acquiring raw materials, to the need of introducing changes into design philosophy (design for AM is free of some restrictions commonly "hard-wired" into traditional industrial design, but new methods introduce few of their own, specific restrictions), establishing new ways of quality control and standardization, developing different component post-processing, integrating of additively manufactured components into existing systems, developing new approaches to life cycle analysis, and different ways of cost and resource management, etc. It is a serious undertaking involving equipment, work force, logistics- essentially all facets of the industrial process. In a way, a new "child" is already conceived within traditional industry and even born, but it takes careful efforts before it matures.

One can outline following specific directions in nearest future of PB-AM aiming at better realizing its potential:

– adaptation and adjustment of existing PB-AM techniques towards;

- production of defectless lightweight parts with high specific strength (beam-based processing);
- production of high-performance alloys with advanced microstructure (BJP), including Ni-based superalloys (powder bed beam-based processing with possible combination with in situ alloying);
- BMGs (powder bed beam-based processing, powder bed BJP processing);
- HEAs (beam-based processing with possible combination with in situ alloying);
- ceramic and non-metal-based composite materials (powder-bed BJP processing);
- metal-based composite materials (beam-based PB-AM and BJP processing);
- compositionally and functionally graded materials (PB-AM both beam-based and BJP processing);

– materials research and development of in situ alloying throughout beam-based PB-AM (EBM and SLM), which can potentially allow using elemental powder and complex powder blends instead of fully pre-alloyed powders as raw materials for production parts made of multi-component metallic alloys;
– material research in the field of a post processing aimed to eliminate residual porosity after beam-based processing for metallic materials, as well as after BJP processing for ceramic, composite and functionally graded materials and BMGs;
– research in optimization of the existing PB-AM production routes aiming at faster and more effective manufacturing;

– industrialization of the approaches to functional optimization of the component design adding functionality criteria (loads, stresses, thermal properties etc.) to shape and weight one within design flow;
– developing common metrology and quality control procedures into the PB-AM manufacturing flow and products standardization aimed to fit the existing aerospace specifications.

6 Summary

The main common development trends of state-of-the-art additive manufacturing production routes application in aerospace can be extracted from the current review and then summarized as follows:
– extending range of the precursor materials, namely: metallic alloys (including HEAs and BMGs), metal and ceramic matrix composites and composite-like materials, lightweight structures and compositionally and functionally graded materials (CGMs and FGMs) used for aerospace applications;
– increasing rate of application trials of various PB-AM techniques for aerospace;
– focus on additive manufacturing of critical aerospace components;
– standardization of regulations of additive manufacturing for aerospace.

Conflict of interests

The authors declare that they have no conflicts of interest in relation to this article.

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