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# A current review on electron beam assisted additive manufacturing technology: recent trends and advances in materials design

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## Abstract
This paper primarily discusses the current capabilities and future trends of Electron Beam Technology (EBT), which is a metal additive manufacturing (AM) process. EBT, comparatively a young technology, is used to produce whole metallic components directly from the electronic data of the desired geometry. Its applications have extended in various industries with broad attention to aerospace and biomedical fields. This paper discusses the diverse prospects of EBT mainly for existing and future materials design. Powder manufacturing and materials characterization techniques are noted down with a focus on powder metallurgical requirements. A vital parameter development platform is also discussed. Finally, the current challenges and the remedies to overcome the challenges with the future outlook are discussed and presented.


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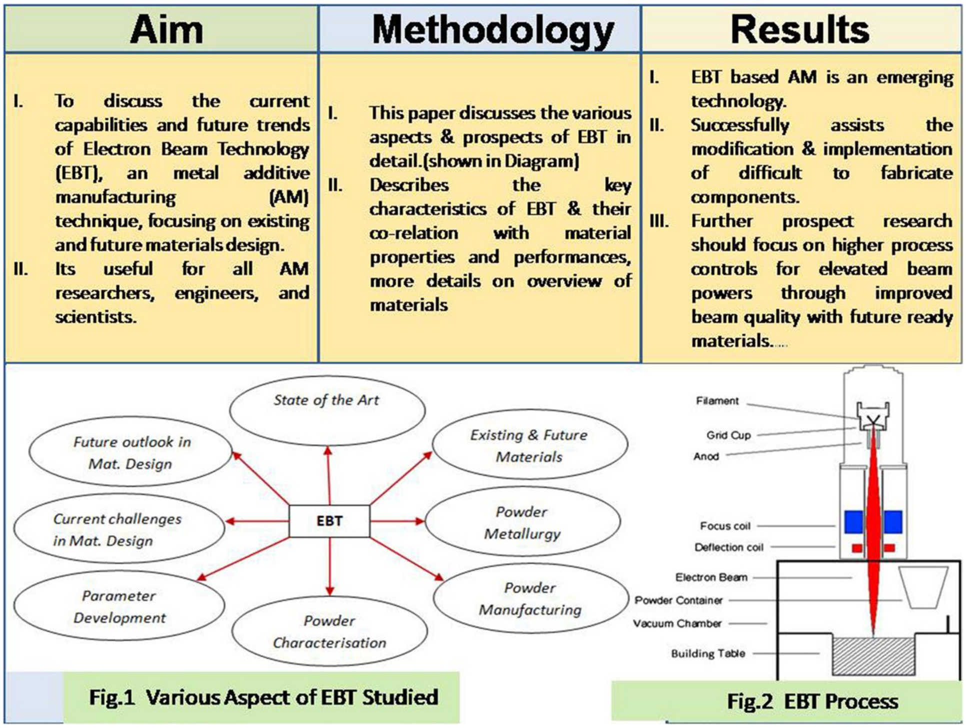
**Graphical Abstract**




**Keywords** Additive manufacturing · Electron beam technology (EBT) · Material development · Material performance · Future materials design etc.

## 1 Introduction

Additive manufacturing (AM) is a 3-dimensional printing method of creating finished products [1, 2]. It makes the use of 3D digital models, generated through various means like CAD, MRI, CT etc., Most conventional manufacturing methods are subtractive in nature. In AM technique material gets added layer by layer, in a systematic and controlled way [3]. There are seven types of additive Manufacturing techniques, categorized as extrusion, vat photo-polymerization, powder bed fusion, binder jetting, directed energy deposition, material jetting, and sheet lamination [4].Innovations in design of materials will permit novel applications for industrial and commercial disciplines. It comprises of all disciplines like medical [5, 6], dental [7], aerospace [8], automotive [9], military [10], food [11, 12], metals & alloys [13, 14], tissue engineering [15–17], integrated circuit technology [18] pharmaceuticals etc. [19, 20] with an extensive range of materials such as solids, liquids, ceramics, powders, pastes, polymers as well as living tissue organisms etc.

In Electron Beam Technology (EBT), the raw material used is either metal powder or wire. Metal powders can be fused to a solid mass by an electron beam, which acts as a heat source. Components are mass-produced in a high vacuum atmosphere with an electron beam by melting the powder. This process creates fully dense components from metal powders with physical characteristics of the target material. EBT recites data from a 3D-CAD model and lays successive layers of powdered material. All these layers are melted simultaneously using a computer-controlled electron beam. Subsequently, it builds up the component. A controlled vacuum process is useful to manufacture components in case of reactive materials which show an enhanced affinity for oxygen [21]. It operates at higher temperatures around 1000 ℃; which leads to differences in phase formation by solidification & solid-state phase transformation [22].

To create a finished product, the solidification phenomenon is linked by laser for the incremental subsequent layers to be get melted. It consists of a directional solidification phenomenon which is different from conventional metallurgical processing [14, 23, 24].

In 1993, EBT was introduced at the university of technology in Gothenburg, Sweden and Arcam was established to become the first commercial system in the year 2002 [25, 26].It builds intricate parts from metal powders at high temperatures and in a vacuum environment. The chemical composition of the material is preserved in a vacuum environment. It offers a good surrounding for building parts using reactive materials like aluminium and titanium alloys [27]. The electron beam ensures a high rate of deposition with uniform temperature distribution within the components; it provides a fully melted metal powder with superior physical and mechanical properties of a finished product [28].

. Recently, consolidated metal powders such as cobalt alloys, Inco-718, and titanium alloys are introduced to manufacture complex parts useful in medical implants, capable of building high-value, low-volume parts with minimum lead times [29].

The present manuscript aims to assess the current and future state of art of electron beam technology. The first part of the manuscript describes key characteristics of the EBT and their co-relation with material properties and performances. The second part gives a detailed overview of materials that have been investigated and may be use in future materials design.

## 2 Electron beam technology (ebt)—state of the art

Additive manufacturing methods open a horizon to innovative design configurations for all structures including cellular structures which offers the lightweight components. The energy produced by the electron beam is high enough for melting a variety of metals and alloys. EBT has the potential to handle several materials like Al and its alloys, tool steel, cobalt-based superalloys, etc. At present, Ti alloys likeTi-6Al-4 V are the highly researched materials for EBT application. Ti alloys have numerous possible applications, because of their superior qualities like high mechanical strengths, low density, high corrosion resistance, human allergic response and better biocompatibility [30]. EBT provides one step manufacturing technique for complex architectures like cellular, meshed, porous etc. Porous customised implants with precise porosity to meet the requirements of the anatomy for medical application can be produced using EBT. Moreover, this hot process yields the components with nominal residual stresses and the vacuum keeps a clean and controlled atmosphere.

Another unique ability of EBT is to produce a negative Poisson's ratio structure, called as "auxetic behaviour". The significance of negative Poisson's ratio is, it heads to higher fracture toughness with shear resistances. Found these ratios ranging between 0.2 and 0.4 and mainly depends on the orientation [31].

Higher manufacturing speed is one of the major advantages of EBT. An electron beam can separately heat the powder at various places simultaneously, Also, laser scans the surface point by point, which considerably speeds up the production.. Due to preheating of powder, it decreases the need of reinforcements and supports during manufacturing. On the other hand, at the powder level, the electron beam is a slightly wider than the laser beam, which lessens the accuracy.

EBT components are given in Fig. 1. Its vacuum chamber's capacity is around $10^{-4}$ torr. The emission of electrons happens at a voltage range of 50 kV to 60 kV by heating a filament of Tungsten. The electron beam focuses on distinct areas of the powder bed. The average particle size is 45–105 μm, which is suitable for complete melting of powder, followed by

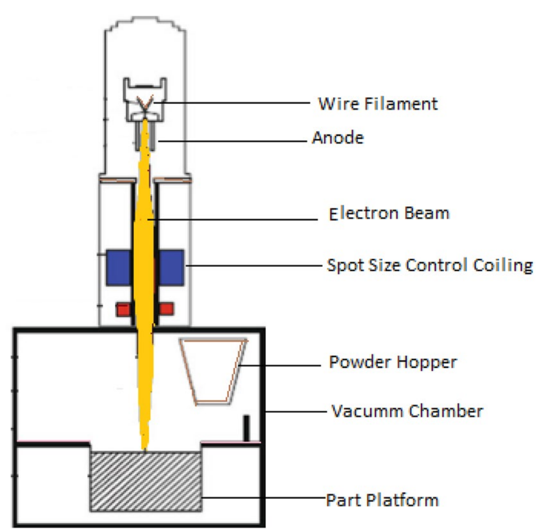



**Fig. 1** Electron beam melting technology (EBT)

re-solidification. The range of electron beam scanning speed varies from 7000–8000 m/s, with the positioning accuracy of ± 0.025 mm and the layer thickness of 0.05–0.2 mm [31–33].

Figure 2 shows the distribution of powder above the start plate. The powder layer is pre-heated using an electron beam, followed through a sequence of scanning operations, which helps to melt the loosely joined powder. The raking system is used to assist the powder to spread and get packed evenly as shown in Fig. 2a.

Uniform melting of powder is necessary for the correct layer thickness [34]. Figure 2b, c shows raked and melt powder layer thickness. The platform gets lowered after completion of one layer cycle, approximately 0.05–0.2 mm, equivalent to single-layer thickness. The process becomes repetitive until the whole build is formed. After completing the process, a helium assisted cool-down progression chain is performed. Material in use and actual build size affect the progression time.

## 2.1 Materials

Materials with good electrical conductivity like 316 L-Steel, Maraging steel, Titanium, Cobalt-Chromium, etc. [35, 36] can be used for EBT applications. More attention is received by Titanium alloys which possess good corrosion resistance, biocompatible properties, and mechanical properties [37]. It offers lightness with strength for automotive and aerospace applications [38]. Commercial grades (99.2% pure) titanium alloys possess an ultimate tensile strength of 435 MPa and offer the vital benefit of being 44% lighter than existing low-grade steel alloys. Titanium is 60% denser than aluminium but more than twice as strong as AA6061-T6 [39]. Ti-6Al-4 V is the finest and well-accepted alloy for almost all types of EBT operations [40, 41].

Inconel 718 Alloy is used for high-temperature applications of AM [42]. It is a nickel-based super-alloy, generally used for gas turbine components, rocket motors, cryogenic storage tanks, pump bodies, jet engines, hot extrusion tooling, nuclear fuel element spacers, etc. This alloy gives corrosion resistance with strength, at high temperatures [43–45].

Table 1 shows the materials and their alloys frequently used for EBT applications [35–45].

## 2.2 EBT-powder metallurgy requirements

There are certain processes by which metallic powder is produced such as gas atomization, plasma induction atomization, Hydride-dihydride process, and the Armstrong process. For AM technology, the powder should have certain characteristics like spherical morphology, high packing density, no internal porosity, high flowability, and compact

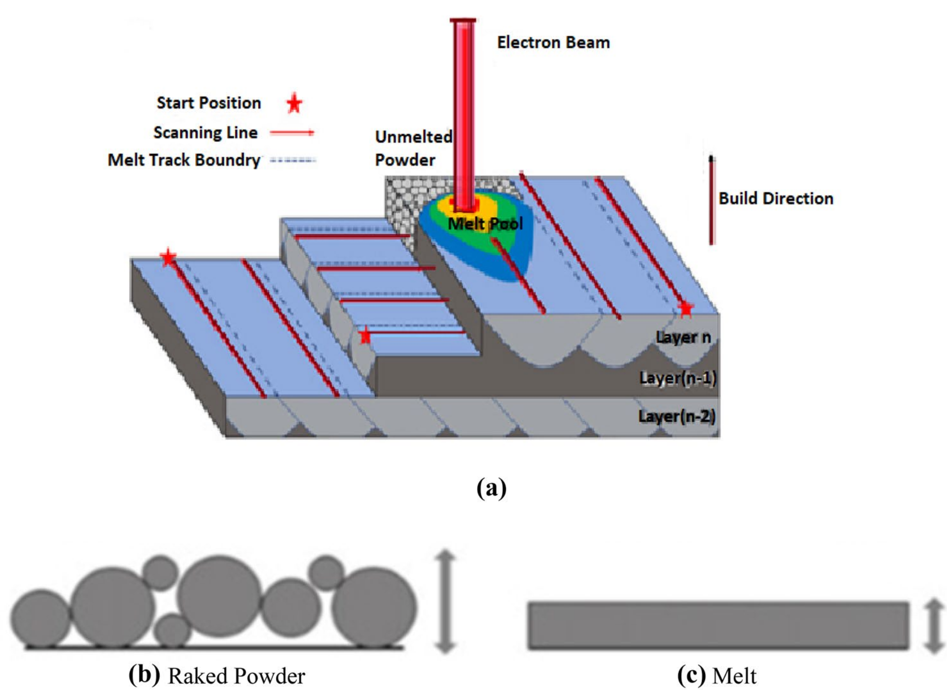



**Fig. 2** **a** EBT melting and raking system **b, c** Powder layer thickness before & after

**Table 1** Materials frequently used for EBT with mechanical properties and its application

| Sr.no | Materials and its alloys | Mechanical properties | Application |
|---|---|---|---|
| 1 | Titanium and chromium-cobalt alloys | Excellent ductility and tensile strength | Biomedical applications |
| 2 | Tantalum | Fully compatible with the human body, Corrosive resistant | Electrolytic capacitors and corrosion-resistant chemical equipment. Clinical instruments |
| 3 | Niobium | Excellent strength/creep performance at high temperature, good thermal conductivity | In superconducting magnets for use in medical MRI machines and NMR machines for analytical chemistry applications |
| 4 | Molybdenum | Excellent strength and mechanical stability at high temperatures (up to 1900 ℃) | Used in steel alloys to increase strength, hardness, electrical conductivity and resistance to corrosion and wear |
| 5 | Tungsten | Good resistance to high temperatures | For making electrodes, heating elements and field emitters, and as filaments in light bulbs and cathode ray tubes, aero-engine valves and turbine |
| 6 | Vanadium | Ductile, good structural strength | Used to make steel alloys, for use in space vehicles, nuclear reactors and aircraft carriers |
| 7 | Zirconium | Strong, ductile and malleable metal, good corrosion resistance | To make crucibles that will withstand heat-shock, furnace linings, foundry bricks, abrasives and by the glass and ceramics industries |

particle size (< 0.010 mm) [46]. It is recommended to use metal powders with 45–106 μm particle distribution that have minimum ignition energy of greater than or equal to 0.6 J [47].

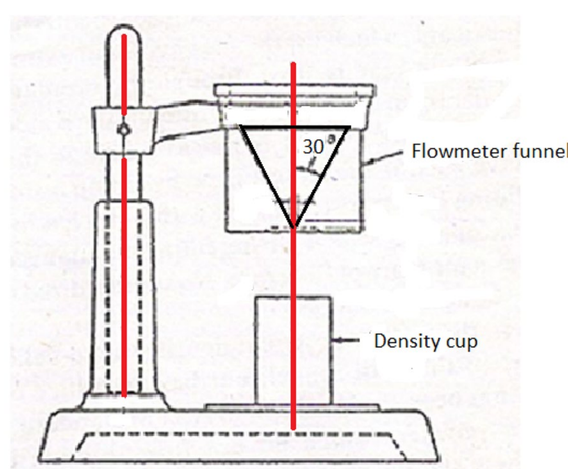
ASTM (B-213) standards are used to determine the characteristics of metal powder [48]. Figure 3a shows the Hall flow meter funnel with a cylindrical brass cup of 25 $cm^3$ and the distance between the top to bottom surface of the funnel is 25 mm. For improved material properties, hopper feeding rate and good powder flowability are recommended [49]. Percentage change in density of material could be analysed with the particle size distribution. A metallurgical stereo-microscope can be used to spot the shape and size of powder particles and also to find foreign particles or contamination [50].

Figure 3 shows the Hall flow meter funnel with density cup. Elevated apparent densities will offer improved heat conduction and consequently, minimizes the possibility of sample over-heating or swelling with quality of support [51]. Internal porosity can be analysed through the sample's cross-section [52].

### 2.3 Brief literature review on simulation studies on metal AM processes

The field of AM has brought the manufacturing process to next level where it made production and product development process easier. An analysis is made on the published research articles on AM simulations. The research gaps and challenges were briefly discuss below. There is a need for having more smarter numerical models which are capable of providing precise calculations for thermal analysis. Need to reduce the computational costs of existing models. Such models will enhance the quality of the produced parts. AM modelling is classified conferring to key performance indicator (KPI), process parameters and the modelling approach (i.e., analytical, numerical or empirical). Specifically, for EBT, thermal modelling, melt pool dimensions are depends on the process parameters like beam speed, power and scan speed [53]. A 3D simulation approach has been developed to address the quality issues of metal-based AM parts. Focused on thermal stresses and deformations. Discuss the different scanning strategies through various case studies [54]. Developed the process models to increase the AM part quality. Different computational and experimental models have been studied with respect to different AM processes [55] 0.2D Finite difference model for the thermal analysis has been presented. It enables calibration of the optimum cooling rates with respect to temperature and porosity. Also shows the future ways to 3D extension of the model [56]. It gives the relationships between process characteristics, material consolidation and component properties with respect to Selective Electron Beam Melting (SEBM) [57]. Provides the literature review on numerical simulation models of the EBM process. Focused on optimization and thermal control by means of process parameters [58]. It discusses the developments in electron beam melting particularly for Ti-6Al-4 V alloys [59]. This manuscript presents the various selection criteria to select the finest AM process (binder jetting/selective laser melting/electron beam melting) for manufacturing a precise component with a well-defined set of material properties [60].

**Fig. 3** Hall flow-meter funnel



## 3 Powder manufacturing techniques

### 3.1 Gas atomization

The gas atomization technique is used to produce fine spherical powders [61]. Figure 4 illustrates the gas atomization process; which consists of dispersing liquid metal through media like air, nitrogen, argon, or helium by a high-velocity jet, as shown in Fig. 4b. Aluminium, copper, titanium, and their alloys, zinc, and magnesium can be spheroidized through this process [62, 63].

Figure 4a shows the sequence of gas atomization of titanium powder produced from liquid titanium through cooling. Similarly, Fig. 4a shows the schematic of various chambers of atomizing process. Inert gases like helium and argon have to be used to avoid oxidation in the case of reactive metals [64, 65].

### 3.2 Induction plasma atomization

The induction plasma process comprises of heating and melting of metal particles through plasma, followed by solidification under controlled conditions. Better control of time provides sufficient time for the molten droplets to solidify, before reaching the bottom surface of the reactor [66]. Nozzle design is important and takes into consideration particle morphology and particle size distribution [67]. The main advantages of the process are improved powder flowability, density, and purity with reduced porosity [68].

In general, flowability is affected by size and shape of metal particles and it is seen that more spherical particles flow easily. Another critical factor is porosity, which can be reduced by re-melting and re-solidifying the material. Uniformly placed re-spheroidized particles enhance the powder tapped density which in turn improves the packing of material [69]. Increasing the plasma melting temperature can improve the powder purity [70]. Figure 5a, b shows re-spheroidized Titanium Powder (Int.), Cristal Global (ITP) CPTI powder sequencing, and schematic illustration of induction plasma process respectively.

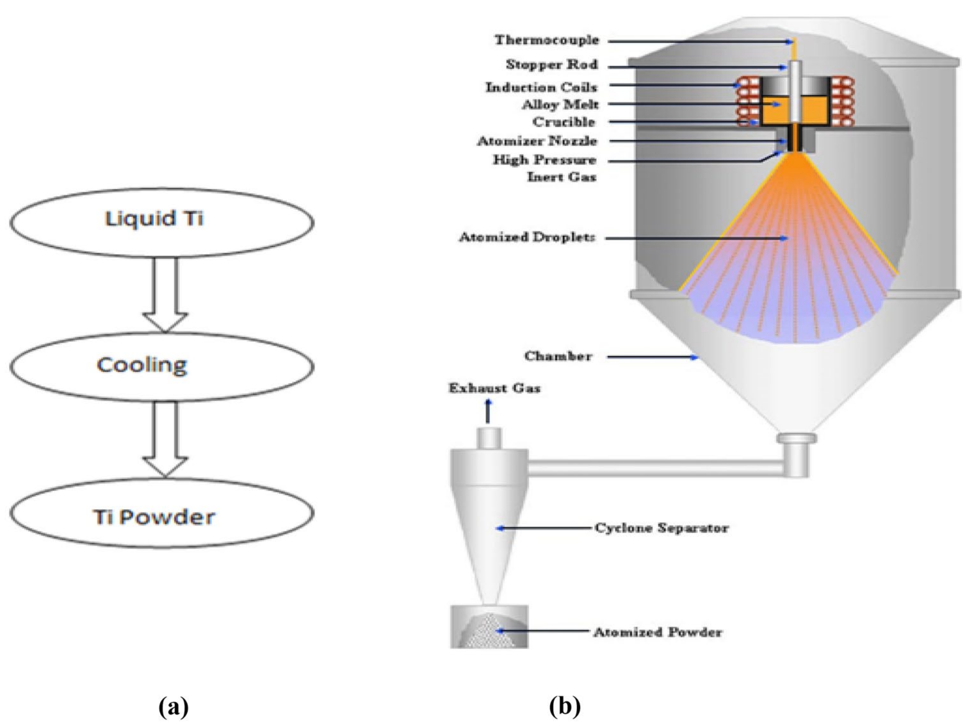



**Fig. 4** Ti-6Al-4 V powder obtained from gas atomization **a** sequence **b** gas atomization process [62]

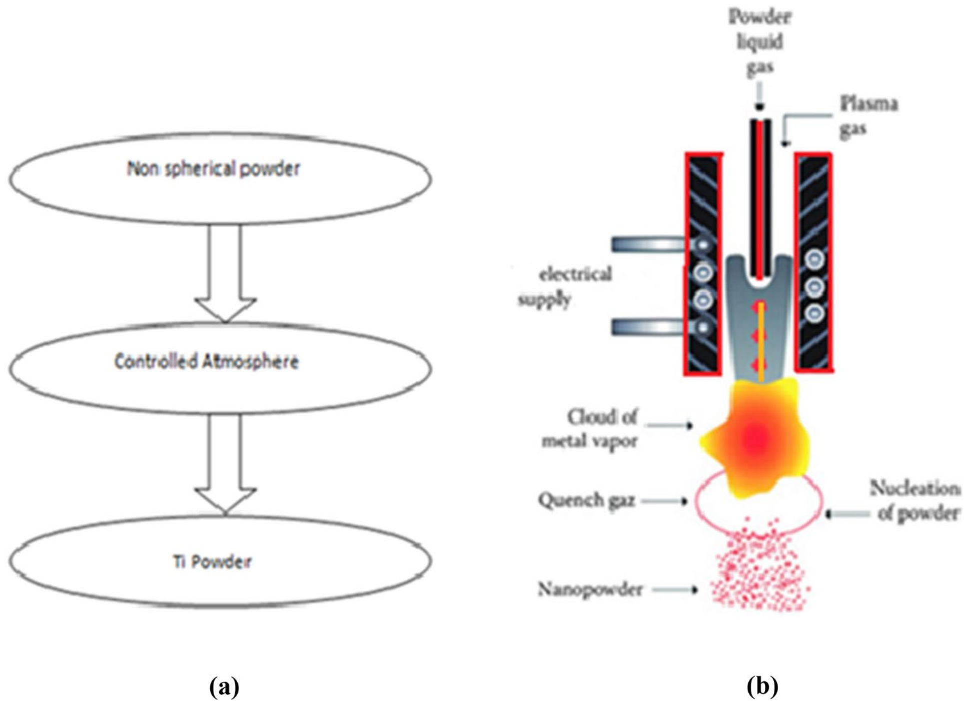



**Fig. 5** Induction plasma atomization processes **a** Sequence of operations **b** Schematic of plasma atomization with re-spheroidized CPTI powder [64]

### 3.3 Armstrong process

This process is best suited for titanium and its alloys but can also be used for broad range of metals, alloys and ceramics. [71–75]. Uniform grain structure and cost reduction are the main advantages of the process with controllable oxygen content with high purity [76, 77].

Roll compact sheets and vacuum hot-press plates can be produced from Ti-6Al-4 V powders [78, 79]. Processing steps are given in Fig. 6. Sodium and Titanium tetrachloride ($TiCl_4$) reaction results into pure titanium and sodium chloride (NaCl). Dedicated vacuum hot press (VHP) is use to make the Ti powder compact. Ultimate tensile (UTS) and yield stresses (YS) are calculated and found to be greater than typical CP-Ti Grade 2 due to equiaxed grain structure obtained at *2–4 Å [80].

Commercially pure titanium (Ti) powder can be produced with the reduction of titanium tetrachloride ($TiCl_4$) and other metal halides by using sodium. It can produce powder particles with distinctive properties with low bulk density. Post-processing activities such as dry and wet ball milling processes, particle size distribution and tap density can be improved. It gives exceptional compressibility and compact properties.

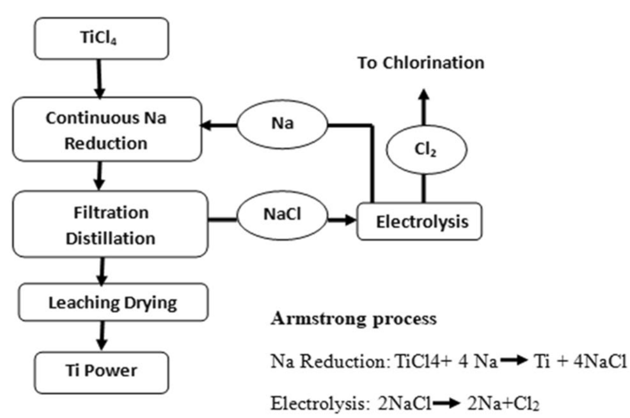



**Fig. 6** Illustration of processing of Armstrong process

### 3.4 Hydride-dehydride (HDH) method

Hydride–Dehydride (HDH) is an advanced technology designed for producing titanium, zirconium, vanadium, and tantalum powders. These metals and their alloys form stable and brittle hydrides that can be crushed, milled and screened to create fine metal powders [81].

Figure 7 shows the HDH process of hydrating titanium at 650 °C. Titanium (brittle phase) gets crushed and milled to form a fine powder. Minimum ignition energy tests i.e., dust/air mixtures performed according to standard BS-EN 13,821:2002 [82, 83].

Table 2 shows the comparison between different powder manufacturing processes [69–83].

## 4 Powder characterization

Prior to parameter development, the powder must be characterized to determine its feasibility for the given process [84]. Electrodes are used to produce the spark of desired energy. Arcam recommends powder with particle distribution of 44–108 µm with the least ignition energy of 0.5 J. The flowability of powder must be such that it should be able to rake up properly in the machine hopers.

Figure 8 shows the initial powder analysis with various characterization steps. Hall flow meter apparatus and density cup are used to measure the flowability and density of powder respectively. The powder should have a density greater than 50% of solid material, it allows to melt the powder and get the fully dense part. Particle size distribution should have a value of around 45 to 105 µm. The smallest particle size is 0.010 mm, to avoid the health hazard [85]. Porosity can be a major problem in titanium alloys as it does not allow entrapped gases to move out of the part during powder melting and solidification [86].

ARCAM AB, a Sweden based company, is the manufacturer of electron beam systems (EBS), which creates solid parts from the metal powders. It is also into the production of various metal powders. It involves powders from different producers using different production processes. A sintering test is used to speck the temperature to preheat the build platform to sinter the powder which is below the platform [87, 88].

### 4.1 Vital parameter development platform

Figure 9 shows the vital process parameter development chart. Build chamber is used to carry out a smoke test. When charge distribution density exceeds a critical limit of powder, smoke occurs [89, 90], causing a powder explosion in the chamber. For the smoke test, parameters can be designed and developed with known parameter window. For smoke-free build, parameters should be within the prescribed window. Line offset, line order, focus offset & beam speed are the parameter settings which are necessary for a "smoke-free" parameter window. Build platform is preheated at a constant temperature and held for 20 min. The current required for preheating can be obtained through a sintering test [91].

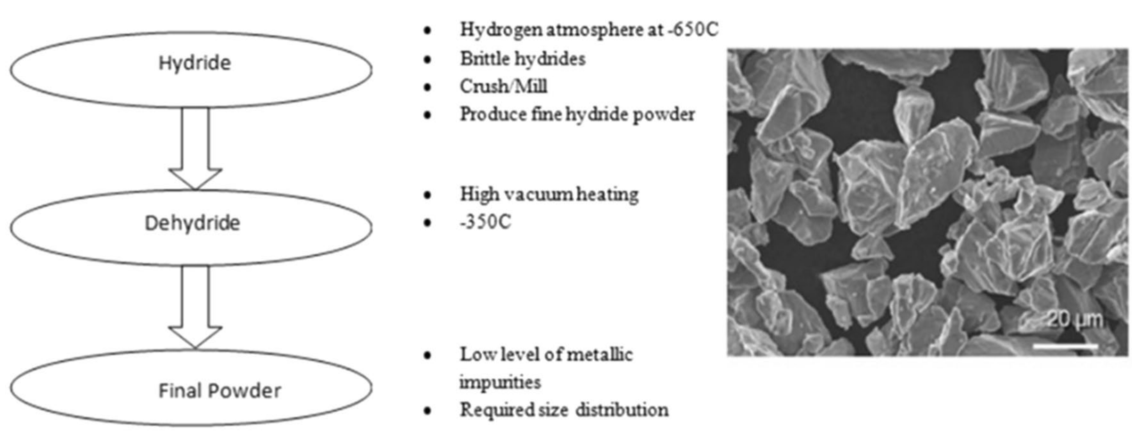



**Fig. 7** **a** Sequence of HDH method **b** Details of HDH **c** SEM image of pure Ti64 [83] powder obtained from HDH

Table 2 Comparison of different powder manufacturing techniques

| Sr.No | | Gas atomization | Induction plasma atomization | Armstrong process | Hydride-Dehydride (HDH) |
|---|---|---|---|---|---|
| 1 | Materials used | Al, Copper, Titanium and its alloys, Zinc, magnesium etc | Titanium alloys etc | Titanium and its alloys, few types of ceramics etc | Titanium, zirconium, vanadium, and tantalum. (Limited to metals which form a brittle hydride) |
| 2 | Production volume | Scalable Technology: very high volumes are available | Very high flow rates: near perfect spheres | Relative flow rate | Relatively low to high flow rate |
| 3 | Cost | Relatively low cost, especially with increase quantities | Relatively high cost | High cost: due to high extraction cost of metals | Low cost |
| 4 | Quality | Excellent metallurgical quality | Excellent metallurgical quality | Relative better metallurgical quality | Excellent metallurgical quality |
| 5 | Particle size (μm) | 0–500 | 0–200 | 0–500 | 45–500 |

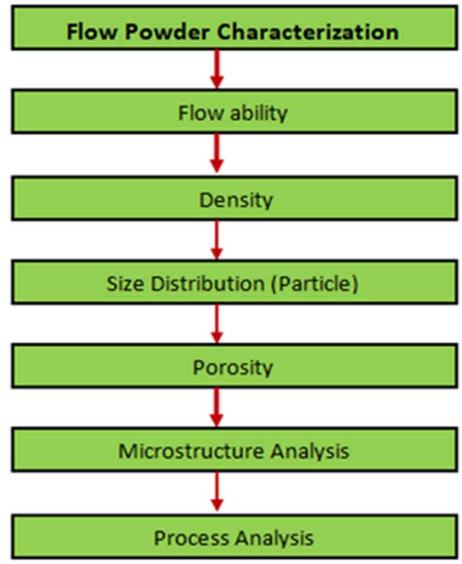



**Fig. 8** Process flow diagram for initial powder analysis

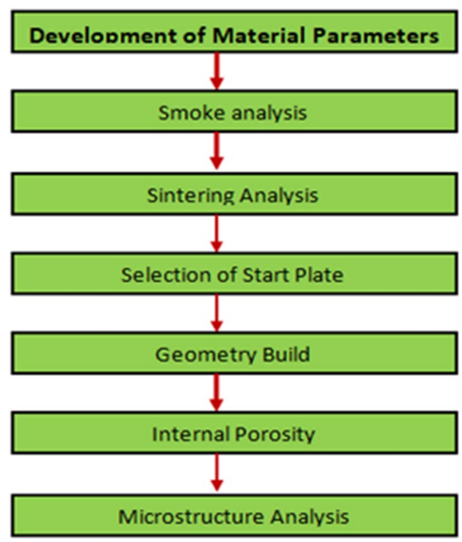



**Fig. 9** Development of vital process parameters

During a build, a start plate holds the powder in place [92]. The material of the start plate should be compatible with new powder material because start plate embraces the powder at place during the build. This plate is insulated by inserting powder below and then levelling it. Sometimes firework occurs when powder explodes with electron beam melting. Fireworks can be reduced with higher process temperatures. For smooth melting new parameters can be developed without any fireworks [27, 93].

By optimizing preheating parameter, as minimum or maximum current value, focus offset, and several preheating repetitions the powder sintering process can be controlled [94, 95]. The use of pre-heat focus offset is to maintain the diameter of the electron beam in preheating.

The focus offset parameter gives the area where the energy is distributed over the surface. A build has to be preheated and use to raise and make stable and optimal bed temperature [87]. All the above mentioned parameters control the temperature and stabilize the powder prior to the beginning of the melting process. The melt process occurs when the powder will liquefy in layers forming the final part. The powder surface should be even and smooth to get the fully dense and final components. The melt speed function and focus offset are the controlling factors. A speed function value regulates the melting speed in automatic mode.

## 5 Current challenges and future outlook in materials design

Despite the above-mentioned significant capabilities of EBT-based AM, the technique has a few challenges, which have to be addressed in the design of future materials.

### 5.1 Overview of current state

AM technology is the future of industrial production. AM offers freedom in design and allows for the creation of optimised parts that are not constrained by the limits of the traditional manufacturing. ARCAM AB reveals a few unique characteristics of the tightly stack parts within the built, in order to increase the productivity. It works in a vacuum environment, which offers numerous benefits like good energy efficiency, enhanced scanning speed, adaptability for many materials and best build reliability. The cost, time, and challenges involved in traditional manufacturing are eliminated; it offers the benefit of readily accessible components for functional testing and installation on a particular system. Broad applications of EBT consist of different control systems for sustainable development like custom aircraft interior components, ducting, combustion engine liners, intricate tooling for composites, fuel and oil tanks and UAV parts, made up of powder sintering [96]. It delivers multifaceted, consolidated components with high mechanical strength [97]. Furthermore, it is useful in novel design configurations for weight-reduction and cellular structures. The electron beams energy density is high enough to melt an extensive array of metals and alloys. EBT has good potential to cope with several material classes which include, aluminium alloys [98], tool steel (H13) [28], cobalt-based super-alloys [32] etc. However, titanium alloys specifically, Ti-6Al-4 V, was the first widely used and extensively researched and used material for EBT [99–101]. Ti-6Al-4 V are used to manufacture highly intricate and functional components, within the aerospace and medical implant industries such as artificial hip joints, knee joints, bone plates, bone ligaments, etc., manufactured through ingot forging, powder processing, by hot-rolling of titanium, etc. [102].

EBT opens a new era for the fabrication of implants from patient-specific customised data with adaptation. It eliminates the costly secondary processing such as machining or forming with related lead times. In addition, it also gives geometric freedom [103]; EBT has enabled one-step fabrications of the intricate architecture of porous, cellular components, which leads to control of the porosity.

Figure 10 shows the statistical development and prediction for all AM technologies. All AM processes will grow with the time but metal-based technologies will be the future of aerospace and automobile industry.

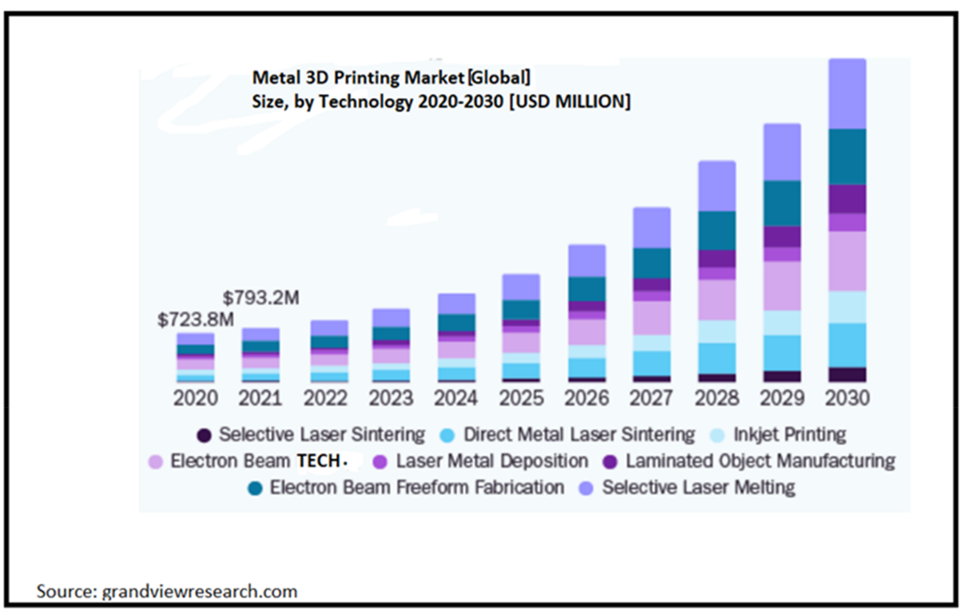



**Fig. 10** Statistical development of all AM technologies

The international market for 3D metal printing was valued about USD 3.52 billion in 2021 and is likely to grow at a compound annual growth rate (CAGR) of 23.9% from 2022 to 2030 [104]

A substantial progress rate for this market is growing through the implementation of metallic 3D printing processes across for aerospace, automobile and other industrial applications.

### 5.2 Future considerations

Additive manufacturing will become the leading mass-manufacturing technique in the future. The full automation and digital workflow are possible with metal additive manufacturing,

Figure 10 shows statistical development of overall AM processes, specifically for AM Prototyping, overall market is expected to grow from $4.4 billion to nearly $20 billion by 2030. Researcher will see it replace with high volume, serial production techniques that require both high resolution and high productivity at low cost.

Despite having impressive advantages as discussed in the manuscript, over conventional manufacturing processes, EBT exhibits process several challenges like part dimensional accuracy and surface finish. Few studies have emphasized the geometric aspects of the process [105]. In the geometric accuracy of metallic test parts manufactured by powder-based electron beam melting processes, few-dimensional errors have occurred which are detected through 3D scanning techniques [106]. The defects in the form of voids and porosity can be significantly improved by the process modifications. This investigation underlines the importance of heat management in various features of the process.

EBT can be used with other metallic materials such as intermetallic, super-alloys, tool steels, copper alloys etc. Metal chips obtained in a high-speed machining have a potential re-use and recycling capability for powder production for EBT. It will help to have more sustainable, eco-friendly and cost-effective additive manufacturing. Specifically, titanium aluminide (Ti–Al intermetallic), has suitable for propulsion exhaust components. Material characterization and micro-structure analysis is essential for parameter development of EBT [107].

Cormier et al. [108] studied the components made by advanced H13 alloy steels for their microstructure and mechanical properties. The components made by EBT, reveal complete inter-layer bonding with no porosity. H13 alloy steel is commonly used as hot-work steel; it gives high-temperature strength necessary for forming tools. Other advantages are toughness; thermal crack resistance, etc. The fabricated material shows martensitic presence with a hardness of 48–50 HRC. After annealing hardness value drops to 20 HRC, therefore a cut-off shrinkage cracks restrained inside a few specific layers as observed [109].

Co-based alloys are specifically useful for medical implants, especially bone implants. Murr et al. [110] investigated, Co-29-Cr-6Mo alloy for its microstructure and mechanical properties. The electron beam produced from the Co alloys prototype reveals a directional and columnar $Cr_{23}C_6$ precipitate architecture parallel to EBT. Its build direction is intermixed with some stacking faults in the FCC matrix. Nickel-based super-alloys offer advantages like corrosion, resistance to high temperature, and oxidation. [111].

Apart from the potential advantages and benefits of EBT, there has been little literature available on process modelling and simulations also the less studied part is the correlation between material properties and its microstructure. A fundamental understanding of the process is important to improve the part quality and process performance. Analytical solution of the process is very demanding because of temperature-dependent material properties and heat source which is moving [112].

AM will also enhance adaptability in other ways as—by making use of different materials, including metal and even ceramics, that to within the same machine. May be Printers will print one object containing multiple materials, paving the future way for significantly widened AM field.

## 6 Summary and future prospects

Additive Manufacturing (AM) is an emerging technology and is believed to revolutionize the future of industrial production. Some of the prominent advantages associated with EBT include reduction of time required for process development, manufacturing of customised items and design freedom. Topologically optimized components, which were difficult to obtain with help of conventional method, can be easily fabricated with additive manufacturing.. The review aims to provide composed and analysed information about additive manufacturing.

In this review article, effort has been made to introduce and discuss in detail the current state, challenges and prospects of the various state of the art technologies available in the domain of additive manufacturing. he review includesvarious research trends of materials, types and needs of different powder manufacturing techniques, powder characterization, parameter development and optimization for EBT have been discussed.

1. Though electron beam technology (EBT) demonstrated its application in various fields like biomedical, automotive, aerospace, etc., still there is scope for enhancement in use of composite materials,shape memory alloys and functionally graded materials (FGM) for more intricate and complex products.
2. This technology enables the integration of digital design and manufacturing. Also successfully assists the modification and implementation of difficult-to fabricate components.
3. EBTs physics is complex and part characterization is sensitive to process parameters, in-depth effect of which may not be well understood yet, future research would help to improve the process.
4. Titanium alloys are widely used for EBT still, other materials like tool steels, intermetallic, Ni-Cu-based superalloys, Co-Cr alloys, etc., have been attempted for a range of applications. Materials performance has to be maximized to utilize the full potential of additive manufacturing.
5. Further prospect research should focus on higher process controls for elevated beam powers through improved beam quality. So far, alloys which have been developed and optimized for forming or casting processes, are successfully used. Besides the development of improved Selective Electron Beam Machines (SEBM), new materials and alloys have to be designed and fabricated in the future.
6. Need of smarter numerical models which are capable of providing precise calculations for thermal analysis. In depth research is required on key performance indicator (KPI), process parameters and the modelling approach (i.e., analytical, numerical or empirical etc.).

**Author contributions** Both the authors have contributed in writing and reviewing the manuscript.

**Data availability** Since this is a review article so data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

**Declarations**

**Competing interests** The authors declare no competing interests.



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