Springer Tracts in Additive Manufacturing

M. Adam Khan
J. T. Winowlin Jappes *Editors*

Innovations in Additive Manufacturing

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Springer Tracts in Additive Manufacturing

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The book series aims to recognise the innovative nature of additive manufacturing and all its related processes and materials and applications to present current and future developments. The book series will cover a wide scope, comprising new technologies, processes, methods, materials, hardware and software systems, and applications within the field of additive manufacturing and related topics ranging from data processing (design tools, data formats, numerical simulations), materials and multi-materials, new processes or combination of processes, new testing methods for AM parts, process monitoring, standardization, combination of digital and physical fabrication technologies and direct digital fabrication.

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Editors would like to dedicate this book to the Management and Administration Team of Kalasalingam Academy of Research and Education.

Dr. M. Adam Khan
Dr. J. T. Winowlin Jappes

Preface

Recently, advances in additive manufacturing and its related work are thriving many researchers to get involved in effective/innovative findings for the past few years. This book entitled *Innovations in Additive Manufacturing* discusses on the history, fundamentals, process development, applications, post-processing and many more experimental results on additive manufacturing techniques. Many engineering applications have started to employ additive manufacturing techniques for component development. Some Industries are using additive manufacturing widely for developing high-end toys and drones for play station. Beyond the research, the additive manufacturing has placed records in developing bio-implants and biomedical instruments. Opportunities have been evolved in post-processing and finish machining of additive manufacturing components. Contents such as surface treatments, modification and engineering such advancements in heat treatment, mechanical hardening and coating, etc., the science of their effects on properties and its characteristics of parts made by them are also covered. Further, simulation, modelling, and optimization of material processing and surface engineering techniques are also focused.

The scope of this book is:

- Fundamental knowledge and research advances in additive manufacturing.
- Covering recent developments and advancements in additive manufacturing.
- Case studies, experimental research, and optimization studies in the current field.
- Unique combination of advanced materials processing and surface sciences.

This book consist of three main parts such as (1) Introduction to Additive Manufacturing; (2) Additive Manufacturing and Materials Development; and (3) Post-Processing and Investigations on 3D Built Materials. Authors of this book are from different countries, and they have made their contribution on research findings and experiences through full length chapters. In Part I, two chapters have been written to cover the history of additive manufacturing along with the basic application and fundamentals. In Part II, there are five chapters to cover the developments of additive manufacturing for metals and non-metals including plastics/polymers. Also, the role of additive manufacturing in biomedical engineering is covered in this part. The post-processing and investigations on additive manufacturing is discussed in Part III. This part covers various aspects on heat treatment, machining, surface finish, surface coatings, electrochemical corrosion, and challenges in additive manufacturing standards.

We appreciate all the contributors for submitting their innovative content extracted from their experience and learnings on additive manufacturing. We would also like to express our sincere gratitude to Springer Team, for their professional support and patronage towards the successful completion of the book on *Innovation in Additive Manufacturing*.

Virudhunagar, India
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Dr. M. Adam Khan
Dr. J. T. Winowlin Jappes

Introduction

This series supports with the information on additive manufacturing process on all aspects of history, applications, development metals, non-metals, biomedical components, heat treatment processing, machining, coating, corrosion and surface science studies. The chapters in this book were reviewed and verified to disseminate the valuable technical content to young researchers, professionals, students, and all interested aspirants on the innovations and latest developments in additive manufacturing for the current scenario.

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Abbreviations

3DP	Three-dimensional printing
4DP	Four-dimensional printing
ABS	Acrylonitrile butadiene styrene
AM	Additive manufacturing
BJT	Binder jetting technology
CDLP	Continuous direct light processing
DED	Directed energy deposition
DfAM	Design for additive manufacturing
DLP	Direct light processing
DMLM	Direct metal laser melting
DMLS	Direct metal laser sintering
DMP	Direct metal printing
DOD	Drop-on-demand
EBAM	Electron beam additive manufacture
EBM	Electron beam melting
FDM	Fused deposition modelling
HAGB	High angle grain boundary
LAM	Laser additive manufacturing
LED	Linear energy density
LENS	Laser engineered net shaping
LMF	Laser metal fusion
LOM	Laminated object manufacturing
LPBF	Laser powder bed fusion
MJF	Multi-jet fusion
PBF	Powder bed fusion
PEO	Plasma electrolytic oxidation
PLA	Polylactic acid
SLA	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering
STEM	Science technology engineering mathematics

WAAM	Wire arc additive manufacturing
WLAM	Wire laser additive manufacturing
YAG	Yttrium aluminium garnet

Part I
Introduction to Additive Manufacturing

Chapter 1
Metal Additive Manufacturing: From History to Applications

Amritbir Singh and Harpreet Singh

1.1 History

In the last 25 years, the additive manufacturing (AM) industry has taken a giant leap of success in the technical world. Earlier, being used only for restricted and few scientific purposes (like prototyping), AM has evolved in terms of material and application flexibility. The technology was first patented and commercialized by Chuck Hull (co-founder of 3d Systems) in 1984 and 1987 respectively [1]. Within four years after the first commercial processing machine, fused deposition modelling (FDM) by Stratasys [2] and STEREOS 400 by EOS [3] contributed to the expansion of the additive technology arena. However, the erstwhile machines, limited to lightweight materials, have prompted some researchers to focus on improving their material versatility. Consequently, the EOS company introduced the first metal processed AM machine (EOSINT M160) to the market based on direct metal laser sintering (DMLS) [3]. The blend of powders was used as feedstock in which low melting point constituent acted like glue to join high melting temperature particles (liquid phase sintering). The chronological order of various firms taking dip into this technology is shown in Fig. 1.1.

Post three years, with an intent to carry out titanium alloy processing, a new firm named AeroMet came into existence. The organization developed a technique entitled laser additive manufacturing (LAM) or directed energy deposition (DED), which uses a high-performance laser to fulfil the purpose as aspired [4]. The material

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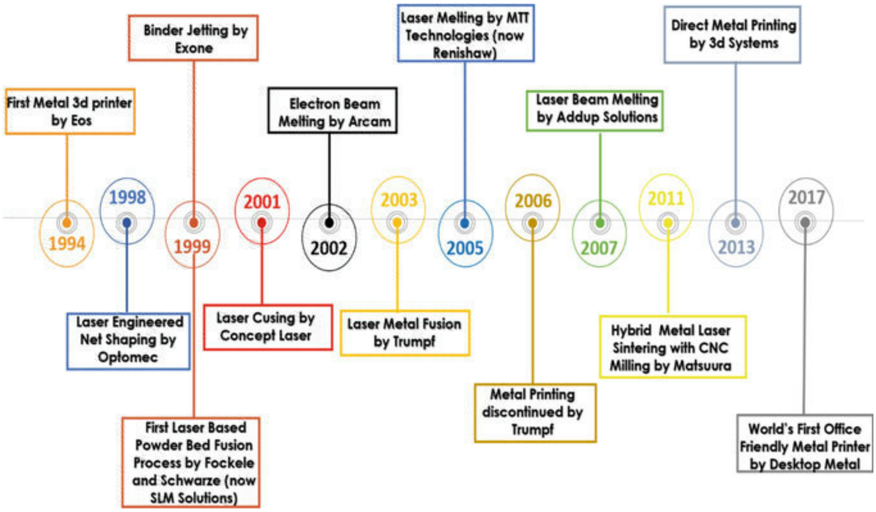

Fig. 1.1 Chronological order of entry of several firms with their respective proprietary names of AM technique in the market of metal 3d printers

processed includes Ti-6Al-4 V, Ti-5Al-2.5Sn, Ti-6Al-2Sn-4Zr-2Mo-0.1Si, and Ti-6Al-2Sn-2Zr-2Cr-2Mo-0.25Si. As the titanium alloy holds its usage in the aviation industry, they produced components for them until it was shut in the year 2005. In 1998, soon after AeroMet, a Mexican company, OPTOMEC at Sandia national labs commercialized the metal printer known as laser engineered net shaping (LENS) worked on the same concept of DED [5]. Moreover, roughly the same year, they achieved a milestone by winning the award for the "top 25 technologies of the year". The following year, ExOne grabs the market attention by introducing the first-ever inkjet-based metal 3d printer, pronounced as binder jetting technology (BJT) [6]. This invention resulted from hard work put up by a group of scientists at the Massachusetts Institute of Technology (MIT) and was first stationed in Motorola. The old type of BJT was soon evolved into an advanced version involving certain technical improvements. These requisite upgrades were made according to the feedback of the consumer. Moreover, in 2000, Frank and Kerstin Herzog established Concept Laser GmbH [7]. They introduced laser cusing (LC) also known as direct metal laser melting (DMLM) at EuroMold in Frankfurt in 2001. In their method, localized melting of stainless steel powder was accomplished layer by layer using yttrium–aluminium-garnet (YAG) laser.

With the growth of metal AM from 1994–2001, it was understood that laser was the backbone for the majority of the production techniques because it was extensively deployed in that timeframe as a driving force for particle consolidation. However, in 2002, Arcam, a Swedish firm, developed a freeform part utilizing an electron beam instead of a laser. Hence, they launched their first production model under the name of electron beam melting (EBM) S12 at EuroMold-2002 [8]. Although the processing of conductive material by electron beam was copyrighted in the year 1993, still it took nine years to get commercialized. Owing to its ability to produce components quickly and cost-effectively, the orthopaedic and aerospace industries acclaimed the EBM and found its utilisation worthwhile. A year after, Trumpf, a German company, introduced laser metal fusion (LMF) machines (TrumaForm LF and TrumaForm DMD) in the market [9]. They manoeuvred laser of 250 watts as heat source plus fibre optics to focus onto pure metal for particle coalescence. Akin to the other machines, their process solely relied on the basic principles of powder bed fusion (PBF). Howbeit, in contrast to other commercialized techniques, it varies in terms of build volume shape (cylindrical). Furthermore, metal 3d printing being a cynosure in the manufacturing field during that period, caught the interest of several other firms. Consequently, on account of the popularity gained by 3d printing in regard to metal AM, these companies from various regions took a step forward to develop their own technique. In particular, laser melting (LM) by MTT technologies in 2005 (presently known as Renishaw) [10], selective laser melting (SLM) by ReaLizer in 2005 (now called DMG Mori) [11], laser beam melting (LBM) by Addup solutions in 2007 [12], SLM by SLM solutions in 2011 [13], Lumex Avance-25 by Matsuura in 2011 [14], direct metal printing (DMP) by 3d Systems in 2013 [15], MetalOne by Sharebot in 2013 [16], LMF by Sisma in 2014 [17], Laser PBF by Aconity3d in 2014 [18] etc. were some of the firms that took a dip into AM processing.

With the addition of the competitive players in the market, the upsurge of innovation in the technology becomes evident. To put it another way, the upgradation of the existing technologies is of considerable significance to meet the customer demands and compete with the rivals. As an example, EOS undergoes various re-developments in their machine to cope up with the present scenario. Likewise, other companies like 3d Systems, SLM solutions, Renishaw, GE Additives etc., did investigation to increase the reliability of the operation by reducing output lead times, expanding build volume etc. Besides, several hybrid systems were developed by integrating AM with subtractive manufacturing, such as CNC machines. The Optomec, Matsuura were some of the companies that contributed to such modernized machines [19]. The firm named Velo^{3d}, facilitated manufacturers to tackle a complex design challenge by providing the scope of support less manufacturing [20]. Further, in an attempt to make metal 3d printers affordable to universities or smallscale industries, Xact Metal constructed a system (XM200C) with the ability to produce diminutive parts [21]. Such a system was capable of performing a task related to direct tooling, prototyping etc. Furthermore, the substantial development of metal printers has captured the market's attention.

Therefore, as a manufacturing engineer, it becomes critical to have an acquaintance regarding the process working. So, the requisite procedural steps of action for achieving 3d printing via discussed commercialized systems are mentioned in the following Sect. 1.2.

1.2 Fundamentals of Additive Manufacturing

The top of the line in metal AM has changed over the last years as it has shifted from developing prototypes to forming end products in industries. Besides, the AM evolved radically in terms of versatility concerning process capabilities and feedstock material. However, to accomplish the building up of mentioned materials, product creation is usually carried out by performing a series of fundamental steps. Regardless of the type of machine employed, these general steps are essential to build the end product and remain consistent with all metal printing techniques. The process series would be broken down into seven main stages (Fig. 1.2) and explained as follows.

1.2.1 Preparation of CAD File and Saving to STL Format

In any event, either the prototype or the part to be built for end-use, the need for a CAD file for AM machine is indispensable. Moreover, if it weren't for 3d design, the birth of AM techniques would not have been feasible. We could only evolve technologies to mechanically replicate solid structures after learning how to interpret them in computers using the software. The very first step in the AM processing for product creation is to envision the appearance of the product. Initially, the component outline will take the form of rough drawings with a blurred indication of dimensions. Once the idea is transformed into appropriate sketching and measurements, it is considered fit for its conversion to digital form via various softwares [22]. Under the

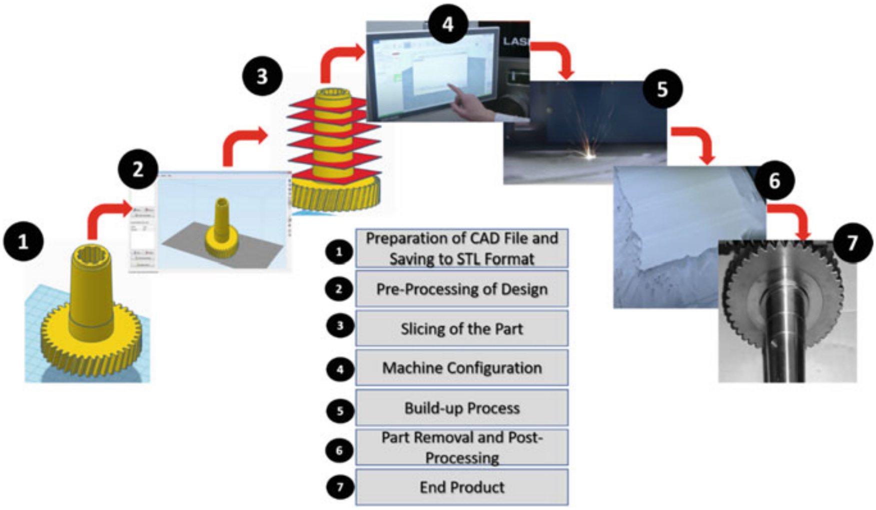

Fig. 1.2 The common sequential steps involved to carry out metal 3d printing using any of the AM techniques

broader umbrella of CAD software packages, SOLIDWORKS, CATIA, FUSION 360°, CREO, AUTOCAD, etc., are widely expended. An open-source application such as TINKERCAD, on the other hand, is readily available as an online platform and deemed easy to use for newcomers [23]. Another option for creating a digital file is to 3d scan an already existed physical part. 3D scanners and photogrammetry tools are the most effective means of assisting the designer in the recreation process [24]. Developing digital models via CAD software or by 3d scanning for AM is only practical if the data is stored in a specific format. This standardized format was created by 3D Systems named STL in the United States and was the first corporation to publicize it in AM technology [25]. This format being copyright, has been rendered a public domain for all CAD providers to conveniently access and hopefully incorporate it into their AM processes. Primarily, this format is explicitly known to describe a design surface as a triangular mesh and therefore referred to as Standard Triangle Language (STL). For several freeform shapes, STL most often prepares accurate and reliable models. However, concerning the presence of unnecessary data and its laborious fixation of inaccurate details are ascribed as its disadvantages [26].

1.2.2 Pre-Processing of Design

After the creation of the STL file and before sending the same to the associated AM machine, a range of measures are required prior to the printing. This pre-processing comes under the subject of utmost importance, regarded as Design for Additive Manufacturing (DfAM). Hence, to make use of this subject, various software solutions are provided by numerous firms. For instance, AMPHYON by ADDITIVE WORKS, 3DXPERT by 3DSYSTEMS, INSPIRE PRINT3D by ALTAIR ENGINEERING, EOSPRINT by EOS, SIMUFACT by MSC etc. are employed widely in this particular field [27]. So, in this step of AM, the part to be printed is virtually positioned and oriented (if required) in the confined space, known as build volume (Fig. 1.3a). With the employment of orientation to the component at a certain angle, support structures become inevitable (Fig. 1.3b). These structures, indeed expended in the majority of the metal AM processes, are also added virtually utilizing the software alluded earlier. The purpose of their inclusion is to stave off the part distortion owing to the residual stresses, printability of overhang features and ensures appropriate thermal conduction. However, their use is often perceived as problematic in terms of part's economics and appearance. Moreover, in regard to the flexibility of software, the designer has the freedom to virtually place the number of parts to be printed at once within the build volume (Fig. 1.3c). Besides, these packages are incorporated in order to get the component printed in the efficient way possible. The efficiency here basically describes the superior properties, cost and time cutting by optimizing the process parameters. The reduction in the aforementioned parameters is relied on the support structure minimization and making an optimal decision on part orientation [28].

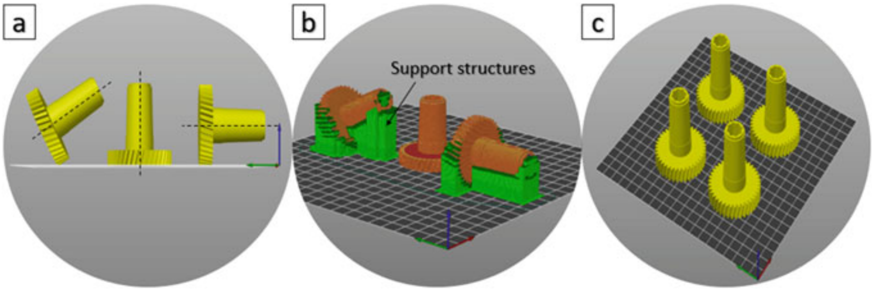

Fig. 1.3 The functions of software provided typically for the subject of DfAM includes **a** part orientation, **b** addition of support structures, **c** ability to fabricate more than one part on a build platform

1.2.3 Slicing of the Part

After pre-processing procedures have been implemented, the following step is to slice the component into the number of 2d cross-sections using previously mentioned software. The slicing partitions the object into several layers to accomplish this process. In essence, it provides ample detail with respect to the path to be followed by the tool in each layer. Such information originates in the form of G-codes and is thus understandable by the AM machine. In other words, slicing a 3d model essentially means the design can be read and printed by a 3D printer [29].

1.2.4 Machine Configuration

All AM machines have specific setup parameters added and exclusive to that system or operation. These parameters, in particular when it comes to metal AM, determine the quality of the component produced for the end application. Therefore, ideal parameters selection of specific material is predominant in the decision making concerning part superiority. In some instances, a component can be built despite an erroneous setup parameter. However, the final outcome in terms of the quality of that component can be unacceptably low. Besides, it is relevant to mention that these machine parameters are introduced in the AM software cited previously. Further, following the loading of the STL file into the AM machine, there are still several necessary system initialization measures to follow. These measures primarily involve the preparation of AM machine for the physical building of part. The manufacturer must ensure that adequate feedstock is laden into the system to accomplish the construction process. Since most of the metal AM machinery uses powder, it is generally filtered prior to the loading by the operator. Although machine setup is not only limited to the material loading but the oxygen content inside the build volume must also be preserved at permissible amounts. Owing to the propensity of the feedstock or molten-pool to oxidize, the necessity of an inert gas environment becomes justifiable. Helium, nitrogen, argon or their mixtures can be expended to minimize the oxidation effects. Consequently, the gas cylinders pressure is to be checked before the process initiates. Howbeit, for the electron based metal AM process, employing these gases can be catastrophic. Thus, for such systems, a vacuum is to be created in an enclosed chamber [29].

1.2.5 Build-Up Process

The machines utilized for creating the component is primarily an automated system and competent enough to perform the vital task. Hence, it can proceed the majority of the time without monitoring. However, from time to time, an inspection of material quantity, power supply, or any other errors is still necessary to ensure proper operational processes.

1.2.6 Part Removal and Post-Processing

After the consummation of the build-up process, the corresponding step is to remove the part from the build plate. Although the part is known to be present inside a cake of powder (particularly for PBF), therefore, prior to the withdrawal, either brush or vacuum system are expended for part cleaning. Following the excess powder elimination, the subsequent course of action is the support removal via hand tools or machines such as wire-electric discharge machining for precision cutting. Consequently, the part face attached to the support lacks surface quality [30]. Owing to this repercussion, post-processing becomes evident. Such processing comprises finishing operations, mainly polishing, sandpapering, coating, etc. [31]. Moreover, AM parts are fabricated to meet the implementation demands. So, most of the time, the part in an as-formed (directly from the machine) state is not considered fit for use and requires further processing like thermal treatment. Several articles have been published in the literature that describes the impact of post-heat treatment on different materials [32–34]. Besides, it is worth mentioning that the type of post-treatment essential on AM part is mainly application-specific.

1.2.7 End Product

After following the requisite action plan, the part printed is ready to go in for practical usage. The application area covers many industries, including medical, automobile, aeronautical etc., and their in-depth discussion is outside the reach of this segment and will be addressed in Sect. 1.5 of this chapter.

1.3 Material Compatibility in Metal Additive Manufacturing

The type of material used for consolidation solely depends upon the laser/electron beam interaction with feedstock. On account of this perfect interrelation, commercialized processing machines, addressed in the Sect. 1.1, are technically sound to form part out of several materials like stainless steels (316L, 304L, 17-4PH), titanium (CP, Ti-6Al-4 V), aluminum and nickel alloys [35]. Even though there exist some alloys from the same family that are not processed effectively owing to its incapability to provide sufficient properties desired for AM feedstock. Accordingly, the study of their physical properties to understand their process feasibility and corresponding formation of molten-pool is of paramount importance. So, some of the significant parameters necessary for the material processing in metal AM systems are as follows.

1.3.1 Melting Point

When it comes to process spontaneity of AM, the melting property of the metal feedstock are crucial. Basically, it's the melting point that decides the material selection in a particular type of AM systems. As already discussed, with the evolution of metal AM, the researchers played a vital role in improving the process capabilities. For instance, a paradigm shift from inefficient thermal sources to high power sources opens up the path for processing high melting point material [36]. So, in a nutshell, the maximum heat source power available governs the type of AM material that can be easily processed. Moreover, most of the material expended in the metal AM is the alloys of iron, nickel, titanium, aluminum etc. In addition, it is well known that these alloys change their state from solid to liquid in a specific temperature range, unlike metals. However, phase depends upon energy density (also known as Andrew's number) produced owing to the heat source at the area of interest. The energy density can either be sufficient to produce the full melting or even low enough to result only in solid state fusion of parts. Besides, the existence of two phases (solid and liquid) can be attributed to the moderate energy density levels [37]. Numerous experimental and numerical validations are presented in the past studies exploring the temperature distribution of heat source over the build platform [38, 39]. In one of the study [40] with Ti6Al4V feedstock, the temperature variation over the powder bed in the PBF process was analyzed. The ability to obtain full and the partial melting region, solid state sintering region, explains the feasibility of Ti6Al4V as AM feedstock. However, materials like tantalum, tungsten or others from ceramic family, owing to its high melting point, require extreme thermal power to get processed. Therefore, AM of such feedstock is non-viable in its purest state, instead needs a secondary material to make them fuse [41]. Moreover, the above concept makes us realize that the low melting point material must be highly utilized as AM feedstock, but that is not the case. In particular, even with a low melting point, copper is as challenging to process as high melting point material [42]. This can be attributed to the fact that the other properties like absorption, transmission etc., are also of considerable weightage in affecting the compatibility of material as AM feedstock.

1.3.2 Optical Interactions

As a visible light of a specific wavelength travels from one media to the next, a well-known pertinent phenomenon transpires. Such occurrence is associated with the optical interactions at the interface of gas and solid medium. As far as metal AM is concerned, one of the main facets is the light interaction with the powder (for the PBF process) over the build platform. This light interaction is nothing but the heat source employed for 3d printing purpose. Moreover, the concerned relation of feedstock at the build surface is quantified in terms of absorptivity, transmissivity and reflectivity [43]. So, to examine the material compatibility with the heat source, there are some questions that require a thorough investigation. It includes how well the material absorbs the spectrum of light used, how much extent the transmission of light occurred in the solid media, and what losses incurred due to the reflectivity at the interface? Fig. 1.4 shows the schematic interaction of the heat source with the

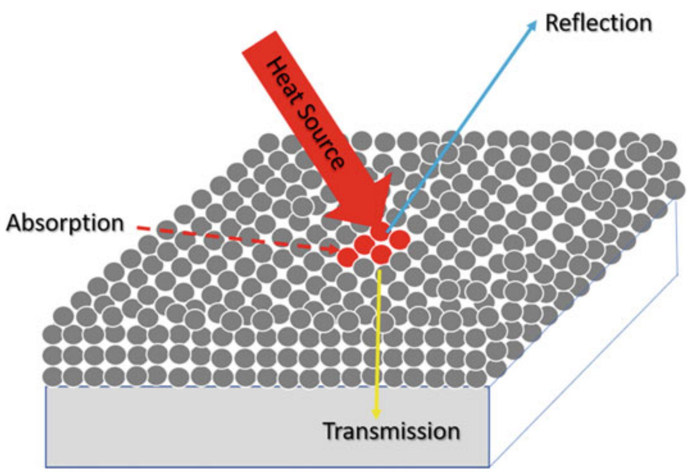

Fig. 1.4 Schematic representation of material interaction with the focused heat source in terms of its optical parameters like absorption, transmission and reflection during the process working

build platform of the PBF process.

The relation between the optical characteristics is given by [44]:

$$A + T + R = 1$$

where A is absorptivity, T is transmissivity and R is reflectivity. A is the ratio of the intensity of radiation absorbed to the total intensity of incident radiation. Likewise, T and R is the radiation intensity transmitted and reflected to the total amount respectively.

Particularly in the PBF process, the thermal source beam is guided over the powder bed with sufficiently high velocity. The process is considered successful only if the heat source–material interaction is adequate enough to melt the powder on the surface to form a melt-pool (relates to absorptivity of material) and to the depth that two corresponding layers should fuse properly (relates to transmissivity characteristic) [44]. Moreover, suppose the powder is comprised of both properties to enough values with the least reflectivity, in that case, the fusion of powder and corresponding layers to requisite depth is achievable, as shown in Fig. 1.5a. On the other hand, the material with better absorption and poor transmission will not form a melt-pool of suitable depth and consequently results in poor adhesion of the adjacent layer (Fig. 1.5b). Further, it was mentioned in the previous Sect. 3.1 that the utilization of copper

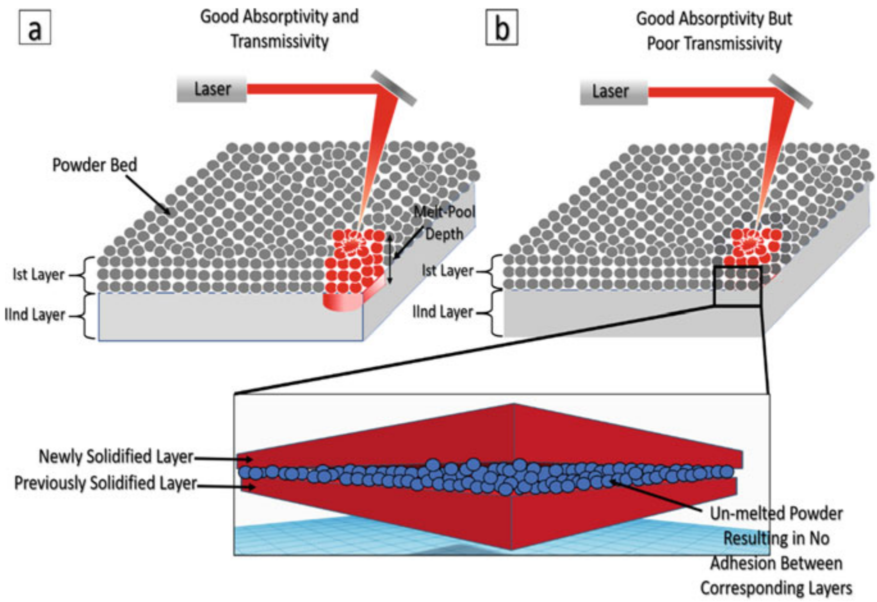

Fig. 1.5 The schematic depiction and effect of material with **a** good absorptivity and transmissivity and **b** good absorptivity but poor transmissivity on the depth of melt-pool or adhesion of corresponding layers in the PBF process

Table 1.1 The list of feasible materials with indispensable properties utilized in the commercialized metal AM systems for energy based processing [35]

Aluminum Alloys	1. Al-7Si-0.6 Mg 2. Al-10Si-Mg 3. Al-12Si
Steel Alloys	1. 316L 2. 17-4PH 3. M300
Nickel Alloy	1. Ni625 2. Ni718
Cobalt-Chrome Alloy	1. CoCrMo 2. CoCrF75
Titanium Alloy	1. CpTi Grade 1 2. CpTi Grade 2 3. Ti-6Al-4 V Grade 5 4. Ti-6Al-4 V Grade 23 5. Ti-6Al-2Sn-4Zr-2Mo 6. Ti-5Al-5 V-5Mo-3Cr 7. Ti-48Al-2Cr-2Nb

feedstock in the PBF process was considered burdensome despite its relatively low melting point than commercially processed materials. This can ascribe to its high optical reflectance and greater thermal conductivity equivalent to 400 W/mK [45]. Although it is relevant to mention that the processing is possible but obtaining defect free copper part is seldom. However, to ease the processing of such materials, different additives are blended with the parent feedstock to enhance their absorptivity and making the process feasible [46].

Besides, considering these compatibility aspects, different firms provided several processable feedstocks utilized widespread in metal AM are shown in Table 1.1

1.4 Processing Techniques for Metal Additive Manufacturing

Metal AM, also known as metal 3D printing, has the ability to significantly alter part with change in design requirements without any difficulty. However, such alterations of product design are considered cumbersome and cost inefficient while processing through traditional methods. Therefore, the customization of parts is an unchallenging task for metal AM and provides enough freedom to perform specific jobs in the industries effortlessly. Moreover, seeking these pros, numerous market players got the attention of this technology in the late 90’s. Presently, the market of metal additive production methods is now widespread and currently available in various forms of technologies. These technologies are classified as shown in Fig. 1.6.