International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-9 Issue-2, December, 2019

Metal Additive Manufacturing by Powder Blown Beam Deposition Process

D. Dev Singh, **Suresh Arjula**, **A. Raji Reddy**

Abstract: ***Additive Manufacturing (AM) is a tool less manufacturing process for building complex components layer by layer. Powder based AM techniques are used for producing porous and dense parts or products by Powder Bed Fusion (PBF) and powder blown Beam Deposition (BD) processes respectively suitable for different applications.***

The present review is mainly focused on the commercially available technology of powder blown Beam Deposition (BD) process for producing fully dense parts, and functionally graded materials used in automotive, aerospace, defense, and nuclear reactors. The properties of BD parts and comparison of the properties of BD parts with Selective Laser Melting (SLM), casting, and Acram's Electron Beam Melting (EBM) parts are presented. This paper provides an insight into the microstructural characteristics and mechanical properties of parts produced by BD process. A brief discussion is presented on challenging issues and applications of BD process. An attempt is made to present available and under development AM testing standards used to evaluate the properties of AM parts. This review also focused on porous parts produced by BD process for medical applications, and metal foil based BD process. Here, new developments in AM process like hybrid manufacturing and 4D printing are also discussed.

Keywords**:** ***Additive Manufacturing, Beam Deposition, Direct Metal Deposition (DMD), Microstructure, Mechanical Properties, 4D Printing.***

I. INTRODUCTION

AM consists of basically three manufacturing methods. They are liquid based, solid based and powder based methods. In liquid based AM, liquid get cured to form objects when it is exposed to laser, or UV light. Whereas in case Fused Deposition Modeling extrusion process, thermoplastic wire filaments are heated to viscoelastic state by a heater and extruded by a nozzle onto a built platform based on 3D CAD model data. According to American Society for Testing and Materials (ASTM) F2792-12, (based on ASTM F42 Committee) Additive Manufacturing (AM) is defined as “processes of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing fabrication methodologies” [1]-[3]. It is also known as 3D Printing (3DP), a revolutionary nonconventional manufacturing technology [3]. AM is a rapid prototyping technique extensively used to build complex structures and intricate shapes without the necessity of post processing. AM is a multidisciplinary field (material science, mechanical and laser engineering, optics and computer science) requiring very close interaction among design, materials, and communication technology. Now, the implementation of AM ideas and concepts are leading from mass production to the customized, need-oriented and eco-friendly production. Applications in the area of aeronautics, automobile, medical field and consumer goods are driving the additive manufacturing into the future. It is important to know about Model, Prototype, Virtual Prototype and Rapid Prototyping. A model is a nonfunctional object and may be constructed at any stage in the product development cycle. It is the proof of concepts, technology or ideas. It can be to any scale, but usually smaller and have only exteriors [4], [5]. A prototype is the first or original example of something that has been developed [6]. This is actually a fully functional version of an intended product, contains complete interiors and exteriors. The process of realizing the prototypes using either an AM or a CNC machine is known as prototyping. Soft or Virtual Prototype is a computer simulated model of a product [6]. It can be tested in the computer system by creating real load conditions on it. But there is no guarantee for the Virtual Prototype to work in actual situation, even though it can be used as a substitute for Rapid Prototyping [7]. Rapid Prototyping (RP) is rapid creation of fully functional 3D physical objects [6]. Its another definition is “RP is the technique for fabricating a prototype from a CAD file using Additive Manufacturing machines.’’ The terms 3D Printing, Additive Manufacturing, Rapid Manufacturing (RM), and Rapid Prototyping (RP) are interchangeably used. 3D Printing/AM is the process, whereas the RP is the end result of it [8]. Different additive manufacturing system developers gave various names to this technology [2], [6], [9]. As of now, there are twenty eight synonyms for AM. They are 1) Additive Fabrication, 2) Additive Process, 3) Additive Techniques, 4) Layer-by-Layer Addition Process, 5) Additive Layer Manufacturing (ALM), 6) Layer Manufacturing (LM), 7) Free Form Fabrication (F3), 8) Solid Free Form Fabrication (SF3), 9) Solid Free Form Manufacturing, 10) Fast Free Form Fabrication, 11) Material Incremental Manufacturing (MIM), 12) Material Incress Manufacturing [6],

Revised Manuscript Received on December 30, 2019.

* Correspondence Author

D. Dev Singh, Research scholar, Department of Mechanical Engineering, Jawaharlal Nehru Technological University Hyderabad, Telangana, India & Department of Mechanical Engineering, CMR Institute of Technology, Hyderabad, India. Email: devsingh209@gmail.com

Suresh Arjula, Department of Mechanical Engineering, JNTUH College of Engineering Jagitial, Telangana, India. Email: arjulasuresh@jntuh.ac.in

A. Raji Reddy, Department of Mechanical Engineering, CMR Technical Campus, Hyderabad, Telangana, India. Email: r_avala@yahoo.com

13) 3D Printing, 14) Material Addition Manufacturing, 15) Material Deposition Manufacturing, 16) Digital Manufacturing, 17) e-Manufacturing, 18) Direct CAD Manufacturing, 19) CAD Oriented Manufacturing, 20) Automated Fabrication, 21) Layer Based Automated Fabrication Process, 22) Instar Manufacturing, 23) Desktop Manufacturing, 24) Fabbing, 25) Layer Manufacturing Technology, 26) Rapid Manufacturing (RM), 27) Rapid Prototyping (RP), and 28) Augmented manufacturing.

There are five steps in any AM processes which are shown in Fig. 1 and are explained here [6], [10]. 1) 3D modeling**:** Desired object can be modeled as 3D CAD solid by using any advanced CAD packages. 2) Covert solid Data and Transfer: 3D CAD model is next converted either into AMF file, STL file, SLC file or etc. and send it to slicing software. 3) Preparing and Checking: Prepare the sliced/layered model using required slicing software, check the errors and adjust the parameters and send the sliced file to AM machine. 4) Building: AM machine can take the file from the computer system and built the part automatically. 5) Post Processing: Essential post processing tasks are cleaning/brushing, post curing and finishing.

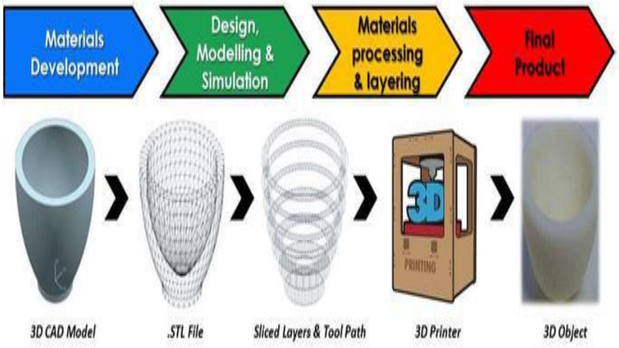

Fig. 1. Steps in basic AM processes [10].

Publications on metal AM are rapidly increased from the year 2007 to 2017.There are nearly 2000 publications on metal AM based on data provided by Scopus [11]. The most of studies were done on Ti-alloys (36.3%) and steels (34.8%). Later the research focused on Al-alloys (15.6%) and Ni-alloys (8.8%). The rest of the research is on Mg alloys, low melting point alloys, bulk metallic glasses (BMGs), metal matrix composites (MMCs), and high entropy alloys (HEAs) was about 4.5% only. The present scenario of additive manufacturing technology usage in different fields is 21% functional models, 16% direct part production, 14% visual aids, 10% presentation models, 13% fit & assembly, 11% tool patterns, 7% metal casting patterns, 5% tooling components and 3% others.

A.Metallic AM Systems

Metallic powder based additive manufacturing systems classified into two groups. They are Powder Bed Fusion (PDF) process and Beam Deposition (BD) process. Powder Bed Fusion (PBF) process is a manufacturing technology, used to manufacture physical components from the intended CAD data on a successive layer by layer strategy [6], [11]-[19]. In this process powder particles irradiated and fused by laser or electron beam. The types of powder bed fusion processes are 1) Selective Laser Sintering, 2) Three-Dimensional Printing, 3) Selective Heat Sintering (SHS), 4) Direct Metal Laser Sintering, 5) Selective Laser Melting, and 6) Acram's Electron Beam Melting.

B. Beam Deposition (BD) Process

The synonyms of Beam Deposition process are Direct Energy Deposition (DED), Laser Metal Deposition (LMD), Laser Deposition Welding (LDW), and Powder Feed Fusion process. Many industries have developed beam deposition processes using laser beam or electron beam as heat source [6], [11]-[13], [15]-[17], [20]. In Beam Deposition (BD) process metal powders and wire feedstock can be completely melted. There are four types of BD processes [21]. The first one is Powder blown based method (Laser beam + Powder delivery nozzle). It is again classified as 1) Laser Engineered Net Shaping (LENS) by National Sandia Laboratory and the U.S. Department of Energy, U.S.A, 2) Direct Laser Deposition (DLD) by the University of Manchester, U.K, 3) Directed Light Fabrications (DLF) by Los Alamos National Laboratory, U.S.A, 4) Directed Laser Fabrications (DLF) by the University of Birmingham, U.K, 5) Direct Metal Deposition (DMD) by the University of Michigan, U.S.A, 6) Laser Metal Deposition (LMD), Chinna, 7) Laser Generation, and 8) Aeromet Corporation's Lasform Technology.

Flow-based method begins with the injection of powder feedstock through the deposition head and heat from laser beam melts the powder for layer by layer deposition until the desired part is built [12], [18], [19]. This method is illustrated in Fig. 2. Laser heats the substrate and creates the melt pool. Then the metal powder is delivered through co-axial annular nozzle of DMD onto the melt pool to create the layer and the process is repeated until the completion of the part. DMD uses co-axial annular nozzle for powder delivery, whereas the other BD processes have lateral nozzles or co-axial two/four jet nozzles. Table I provides the details of powder flow-based LENS and DMD processes inventors, research organizations, industries, universities, patents and current manufacturers.

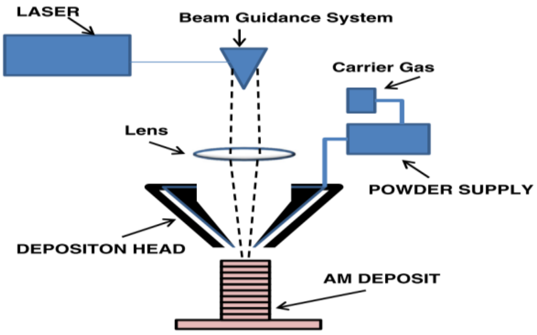

Fig. 2. Flow-based BD illustration scheme [18].

The second one is wire based method (Electron beam/Laser beam + Metal wire feedstock). It can be categorized as 1) Wire-Based Electron Beam Metal Deposition (EBMD-W), 2) Electron Beam Freeform Fabrication (EBF3) by Lockheed Martine, (Bethesda, MD) and Sciancky, Inc., 3) 3D Cladding, 4) Shaped Metal Deposition (SMD), 5) Selective Laser Cladding (SLC), 6)

Wire-based Laser Metal Deposition (LMD-W), 7) MER plasma transferred arc selected FFF(PTASFFF), and 8) Laser Metal Deposition Shaping (LMDS) by Chinese Academy of Sciences & Shenyang Institute of Automation. This technique enables to build large scale products due to high deposition rate and volume, but it creates a rough surface and imprecision dimension. Whereas the third deposition method can combine powder and wire feedstock, and last method can do deposition by pre-placed powder and wire feeding.

Table- I: History of powder blown
Beam Deposition (BD) process

S. No	Process	Beam Deposition(BD) Process	
		Laser Engineered Net Shaping (LENS)	***Direct Metal Deposition (DMD)***
1	Founded (in year)	1992	1993
2	First granted U.S patent (in year)	6,046,426 (1992)	7,765,022 (2010)
3	Inventor	---------------------------	Mazumder group
4	Company	Sandia National Laboratory, U.S.A	University of Michigan (Mazumder Group), U.S.A
5	Head Quarter	Albuquerque (U.S.A)	Michigan (U.S.A)
6	First system introduced	1997	2010
7	Feed stock	Metal Powders	Metal Powders
8	Exist	1997: SNL given permission to Optomec Inc. for mfg. of LENS machines	University of Michigan (Mazumder Group) given permission to POM group Inc. for mfg. of DMD machines
9	Initial target	Industrial	Industrial
10	Current manufacturer	Optomec Inc., U.S.A	M/s POM Inc. U.S.A

II. AM TESTING STANDARDS

In the 1990's, when rapid prototyping technology was still mainly focused on formal/functional prototypes, the AM community started to be concerned with the development of standards for AM. The current standards applied with regard to conventional manufacturing processes (machining, welding, casting, etc.) or materials (in all forms) do not suitable for additive manufacturing processes. Because additive manufacturing involving with various techniques, materials characteristics and operational parameters, which can greatly influence the final quality and properties of the part.

Despite the absence of AM standards, conventional standards are commonly used in AM processes, inspections and testing [22]. It must be noted that not all the tests necessarily correspond to an official standard (International Organization for Standardization [ISO], ASTM, Deutsches Institutfür Normung [DIN], etc.), and test methods. Some researchers used their customized tests, and they do not even mentioned standards in the literature. ASTM E-28M (Mechanical) was carried by E28.16 Rapid Prototyping subcommittee as an AM standard.

ASTM Committee F42 on Additive Manufacturing Technologies was formed in 2009 with many subcommittees [1], [10]. These subcommittees approved few AM standards and some are still in developing stages. This committee, with a current membership of approximately 100 experts mainly from America and EU doing the promotion of knowledge, stimulation of research, and implementation of technology through the standards development for AM technologies. The F42 committee comprises these subcommittees: F42.01 Test Methods, F42.04 Design, F42.91 Terminology, F42.94 Strategic Planning, and F42.95 US TAG to ISO TC261.

ISO Committee TC 261 on Additive Manufacturing Technologies was established in 2011. ISO TC261 is formed from 16 participating countries and five observer countries. The committee has four technical subcommittees: ISO/TC 261/WG1 Terminology; ISO/TC 261/WG2 Methods, Processes, and Materials; ISO/TC 261/WG3 Test Methods, and ISO/TC261/WG4 Data Processing. Despite both ISO and ASTM committees working separately on their respective standards, during a meeting held in Nottingham, UK in July 2013, both the committees agreed work together for developing AM standards.

III. METAL POWDERS AND MECHANICAL PROPERTIES

A. Pure Metal Powders

Pure metal powders are not suitable for powder blown BD process and also for PBF process due to the following two reasons. First one is limited mechanical properties and poor anti-oxidation/anti-corrosion capabilities. Second, partial melting of metal powders did not show significant progress in a particular application [20]. LMD is normally used for producing fully dense parts with complete melting of metal alloy powder particles. Functionally graded complex shaped porous load bearing implants of pure Ti and Ta with partial melting of metal powders using low laser power is also possible by LMD as shown in Table II.

Table- II: Pure metal powders processed by LMD process [20]

Metal powders	Powder characteristics	Process	Laser type	Bonding mechanism	Mechanical properties
Ti	Commercially pure; particle size 50-150µm	LMD	Nd : YAG laser, 500W	Partial melting of powder surface (avoid complete melting of powder to form desired porous structure)	Porosity 35-42 vol.-%; Young's modulus 2-45GPa; 0.2% proof strength 21-463MPa (similar to human cortical bone)
Ta	99.5% purity; particles size 45-75µm	LMD	Nd : YAG laser, 500W	Partial melting of powder surface (avoid complete melting of powder to form desired porous structure)	Porosity 27-55 vol.-%; Young's modulus 1.5-20GPa; 0.2% proof strength 100-746MPa

B. Alloy Powders

A majority of AM research effort was focused on Ti based, Ni based, and Fe based alloy powders as reviewed in Table III [20]. The AM research also focused on Al based alloys to face challenges in the laser processing of nonferrous alloys. Nd: YAG laser, fiber laser and high powered CO_2 laser are generally used for good bonding mechanisms. Alloys of Ti based, are being mainly used in the applications of aeronautical and medical fields, due to their good chemical and mechanical properties.

High performance components in jet engines and gas turbines are additive manufactured using IN625, IN718, and Rene 41, 88DT powders (Table III).

The parts made by these alloy powders have good creep, corrosion resistance, and tensile properties. LMD processed Rene 41 had ultrafine directionally solidified columnar grains of arm spacing ~35µm due to high thermal gradient and cooling rate as shown in Fig. 3.

Table- III: Alloys powder processed
by DMD/LMD processes

Alloy	**Compositions**	**Powder characteristics**	**Process**	**Laser type**	**Mechanical properties**
Ti based	Ti-6 Al-4 V	Gas atomized; spherical shape; particle size -100 +325 mesh	DMD	CO_2 laser, 6 KW	Tensile strength 1163 ±22MPa, yield strength 1105±19MPa
Ti based	Ti6Al4V	Spherical shaped; particle size 25-45µm	LMD	Nd : YAG laser	Tensile strength 1211±31MPa; yield strength 1100±12MPa; elongation 13.0±0·6% (annealed); Young's modulus 118.000±2.300MPa
Ti based	Ti-25 V-15 Cr-2 Al-0.2C	Gas atomized; oxygen content 0.19 wt-%	LMD	CO_2 laser, 1.75 KW	Tensile strength 1100MPa/20^{0}C; ductility 2-4%; fatigue properties 650MPa/450^{0}C, 300MPa/550^{0}C, 200MPa/650^{0}C
Ti based	Ti-4 Al-1.5Mn	Argon atomized; spherical shape; particle size 45-420 µm	LMD	CO_2 laser, 5 KW	Impact toughness 599 ±57 kJ m^{-2} (as deposited), 888 ±33 kJ m^{-2} (955^{0}C annealed)
Ni based	Inconel 625	Gas atomized; powder diameter 45-135µm	DMD	CO_2 laser, 6 KW	Free from defects like crack, bonding error or porosity; as deposited microstructure mostly consists of columnar dendrites; very high hardness 254±6 HV
Ni based	Inconel 718	Gas atomized; spherical shape; particle size 44-150µm	LMD	CW CO_2 laser, 5 KW	Tensile strength 845MPa (as deposited) and 1240MPa (heat treated); 0.2% yield strength 590MPa (as deposited) and 1133MPa (heat treated); elongation 11% and reduction in area 26% (as deposited)
Ni based	Rene 88DT	Particle size 44-150µm	LMD	CW CO_2 laser, 5 KW	Tensile strength 1400-1440MPa; 0.2% yield strength 1010-1030MPa; elongation 16.5-17.5% and reduction in area 17.5-18% (HIP +heat treated)
Ni based	Rene 41	Argon atomized	LMD	CW CO_2 laser, 8KW	Tensile strength 855MPa; yield strength 682MPa
Fe based	Tool steel H13	Particle size -70 mesh	DMD	CO_2 laser, 4.5 KW	Maximum hardness 690HV; yield strength 1505MPa; ultimate strength 1820MPa; failure strain 6%; reduction in area 10%
Fe based	AISI 4340 high strength low alloy steel	Gas atomized; mostly spherical shape; particle size 2140±325 mesh	DMD	Fiber coupled diode laser, 1 KW	Maximum porosity 4.13%; microhardness 681-480 HV; Microhardness decreases and amount of tempered martensite increases from the upper to the lower layers
Fe based	Stainless steel 316L	Spherical shape; particle size 53-1173µm	LMD	-----	Porosity 5.07 vol.-%; tension modulus 193.47GPa; yield stress 419MPa; ultimate tensile strength 826.9MPa; failure strain 28.95%
Fe based	Fe-15Cr-2Mn-1 etc. (at-%)	Gas atomized; spherical shape; particle size 10-110µm	LMD	CW Nd : YAG laser	Microhardness ~900 HV (9.52GPa)

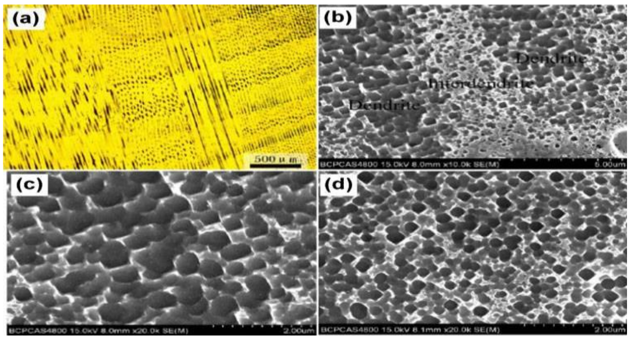

Fig. 3. (a) Longitudinal microstructure of LMD processed Rene 41, (b) size difference of γ' precipitate in (c) cellular dendritic and (d) interdendritic regions[20].

The research reports showing on additive manufactured iron based alloys (i.e. steels) are many, but the progress is not significantly enough. Fully dense components of AM steels are still in the developing stage. A very little research is available on Al based alloys processed by LMD [20]. Because Al based alloys have high reflectivity, high thermal conductivity, thereby increasing the laser power for melting the powder. Intermetallic, multilayer parts and FGMs can be produced by LMD process. Researches on intermetallic parts are growing in the powder blown BD process (Table IV).

Table- IV: Multicomponent metals/alloys powder
systems processed by LMD processes [20]

Category	**Materials system**	**Powder characteristics**	**Process**	**Bonding mechanism**	**Mechanical properties**
Intermetallic	Compositionally graded Ni-Al	Gas atomized Al and water atomized Ni; both particle sizes 45-75µm	LMD	Complete melting of powder; in situ reactive alloying	Solidification and sub-solidus cracking; susceptibility and porosity
Intermetallic	Compositionally graded Ni-Al	From elemental Ti to 23.2 at-Ni%	LMD	Complete melting of powder; phase evaluation $\alpha \rightarrow \alpha+\beta \rightarrow \alpha+\beta+Ti_2Ni \rightarrow \beta/B2+Ti_2Ni$	-----
Intermetallic	γ-TiAl, Ti-47Al-2.5V-1Cr (at-%)	Normal powder blends composition of 52.04Ti-47.96 Ni	LMD	Pre-alloyed powder full melting	Fully dense parts tensile strength in longitudinal direction was 600-650MPa & in transverse 550-600MPa

C.Metal Powders Production Issues

Some material processing issues are encountered during additive manufacturing processes, which affect component quality directly the due to process parameters and materials interaction.

These are common in all types of additive manufacturing processes. Some of the material processing issues such as porosity, densification level and residual stresses are presented here [20].

Porosity

Porosity (between layers, in the bulky layers and in overlapping of layers) is a defect occurring in almost all work pieces manufactured by metallic AM processes [15]. It can be powder induced or process induced (Fig. 4). Powder-induced porosity is due to powder production methods like gas atomization (GA), plasma rotating electrode process (PREP), and plasma atomization (PA). During these processes, powder entraps inert gases in it. The main reason for the generation of porosity is the part processing methods. So, process parameters such as laser powers, traverse speeds, and thickness of layers must be selected correctly to avoid creation of pores. From the optical microscopy, as shown Fig. 4, the size of the process induced porosity bigger than the powder induced porosity. Porosity and also surface roughness are significantly promotes fatigue crack initiation locations [23].

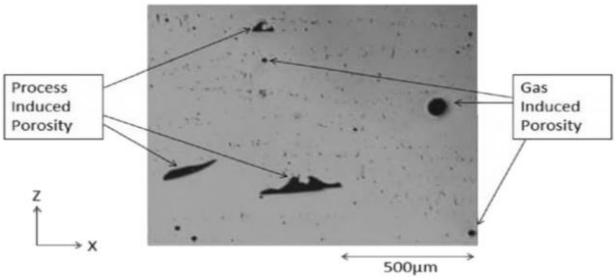

Fig. 4. Process-induced and gas-induced porosities came from the metal powder feedstock examined by Light Optical Microscope [17].

Densification Level

Mechanical behavior of AM parts is determined by densification level (Table II-IV). The densification of AM parts depends on laser powder (p), scan speed (v), hatching (h), and thickness of layer (d or t). For calculating densification level by the combined effect of these parameters an integrate factor introduced as Volumetric Energy Density (VED, KJ/mm^3) is defined as VED~P/vhd. It can also expressed as E=αP/vht. Here α is absorptivity [23]. The density of parts increases due to increase of laser power at lower scan speed, hatch spacing and layer thickness or vice versa.

Residual Stresses

Residual stress is the internal stress locked into a material caused due to uneven heating and cooling process. These stresses are present even after all external forces have been removed. Phase transformations in AM parts lead to residual stresses and its magnitude and shape profile depends on geometric height of the component, materials properties (elastic modulus and coefficient of thermal expansion), laser scanning and processing conditions. The residual stress in the form of tensile stresses is more at the top faces of the specimens, which is almost equal to yield strength. With the addition of extra layers of materials on previous layers, these tensile stresses are converted into compressive stresses due to repetitive heating and cooling. The residual stresses are more along the scan direction due high thermal gradient than the perpendicular direction [23]. Accumulation of residual stresses in the parts can lead to cracks and debonding of inter layers. The combined formation of microscopic and macroscopic cracks can lower dimensional accuracy, ductility and strength of AM fabricated parts [15]. There are several methods to measure residual stresses. They are X-ray diffraction, micro-hardness, and neutron diffraction. Residual stress levels can be reduced by preheating of substrate, which contains low temperature gradient.

D.Mechanical Properties

From published data, mechanical properties such as yield strength (YS), Ultimate Tensile Strength (UTS), etc. of as built and machined parts are given in Table V [3]. The properties EBM, SLM and LMD parts are compared with the conventional cast and wrought parts. The EBM processed components showed superior mechanical properties over the casting parts and almost equivalent to wrought work pieces. SLM parts on the other hand have higher UTS and YS than EBM, wrought and casting parts but less ductile. UTS and YS of LMD and SLM parts are higher than EBM, wrought and casting samples. SLM specimens showed almost equivalent mechanical properties with LMD. Higher fatigue strength and low fatigue toughness for as-deposited LMD and SLM components of Ti6Al4V than EBM Ti6Al4V parts due to fine α′ martensite. The EBM, SLM and LMD processes are high energy metal Additive Manufacturing methods used for producing dense structures applicable to different applications [23].

Table- V: Comparison of mechanical properties of EBM, SLM and LMD

Processed methods	Alloy powders	YS (MPa)	UTS (MPa)	Percentage of Elongation	Hardness value (HV)
Wrought	Ti-6Al-4V ELI	861	932	15	328
	Ti-6Al-4V	861	931	11	------------
Cast	Ti-6Al-4V ELI	735	852	4.5	334
	Ti-6Al-4V	759	861	9	-------------
EBM	Ti-6Al-4V ELI	930	970	16	318
		869	928	9.9	327
	Ti-6Al-4V	950	1020	14	327
		883-938	993-1029	13.6-14.2	------------
SLM	T-i6Al-4V ELI	1143	1219	4.89	403
		996 ±10	1110 ±13	7±4	399±4
	Ti-6Al-4V	990 ±5	1095±10	8.1 ±0.3	------------
		1116±61	1286±57	8 ±2	384 ±4
LMD	Ti6Al4V ELI	1062	1157	6.2	------------
		976 ±24	1099 ±2	4.9 ±0.1	360 ±10
	Ti-6Al-4V	1025-1085	1138-1168	3.4-3.7	390 ±2
		973	1077	11	------------

A Zadi-Maad, et al., described mechanical properties of several types of stainless steels (304, 316, 321, 347, 420, 17-4PH), tool steels (H13, M2 HSS), maraging steel (18Ni300), low-alloyed steels (4140, 4340) processed through Powder Bed Fusion and powder blown BD process [18]. Tungsten carbide, Stallite, tool steel (P20, P21, S7, D2), and IN600 are also proceed by BD method. The SLS process is used to manufacture components with wide range of materials [22].

The effect of co-sintering process on densification and microstructure evaluation at the interface in the two layered graded composite of IN718 and IN625 are produced by SLS and DMLS. It is used in conjunction with a powder layering technique such as LENS/DMD/LMD [24].

Anisotropy for different built direction (such as side built, top built and flat built) suggest that flat-built Ti-6Al-4V specimen (ASME E8 M-04) produced by ARCAM A2 EBM machine are superior to all regarding with strength, elastic modulus and minimum anisotropy was proposed by Leila Ladani, et al., [25]. Whereas the top built direction of the parts in DMD process have better mechanical properties.

SLM (KU Leneuven-PMA SLM machines) used for producing inner cavities, inclined and horizontal downfacing areas, as experimented in Al-Si-10Mg parts by Raya Mertens, et al., [26]. Here, 300W Ytterbium fiber laser with 80µm spot size and 1400mm/s scan speed used for producing 95% dense parts. SLM process is the next alternative to EBM for producing dense components. Whereas the BD processes used for manufacturing of fully dense parts.

Nesma T. Aboulkhair, et al., [27], Xuesong Han, et al., [28], Omar O. Salman, et al., [29], experimented that the Selective Laser Melting (SLM) process is also used for manufacturing 99% dense AlSi10Mg parts, and $316L/CeO_2$ composites. But the processing of dense Al alloys by LMD process is difficult, due to its high reflectivity and energy obserbivity [29]. Prajakta Subhedar [10], and KaufuiV.Wong, et al.,[30] presented papers on the various AM processing methods. A review on the evaluation of mechanical properties of CP-Ti and α-βTi alloys processed by SLM and LMD based on the response of process parameters by P. Chandramohan, Shepherd, et al [31].

Valmik Bhavar [32], and B. Kieback [33] stated that the functionally gradient materials (FGM) were innovative materials and their final properties changes gradually with varying dimensions and positions. Materials developed from metals to composites are in use today. The statistical analysis was carried out by Subodh Kumar, et al., [34] on direct metal deposition for predicting the deposited heights for three control variables. The selected control variables are laser power (1.0, 1.25, 1.5) KW, laser scan speed (0.3, 0.5, 0.8) m/min and mass flow rate (5, 8, 11)g/min. Taguchi's Design of Experiments (L_9 Orthogonal array) was used for this purpose. S/N ratio and ANOVA, regression analysis had done to build height deposit models for predicting height deposit in DMD with different control variables.

Hardness of AM parts is a commonly investigated mechanical property (Tables II-IV). In almost all the cases, hardness values of fully dense LMD parts are higher than conventional powder metallurgy or any cast parts and possesses better wear resistance. Processing of Fe-Cr-C-W metal matrix composites by DMD process leads to the development of suitable alternative materials for wear resistance cobalt bearing alloys. [20]. H.M. Gajera, et al., [35], and Chetan kumar M. Patel, et al., [36] proposed CL50WS materials are an attractive alternative materials as they do not suffer from corrosion and cracking because it has more nickel and low carbon. DMLS processed Ni has better corrosion and wears resistance.

A comprehensive study was done by Qingbo Jia, et al., [37] on densification behavior (lower density at low laser energy and nearly full 98.4% density at 330J/m), microstructure, micro-hardness with increased mean value of $395.8HV_{0.2}$, wear performance and high temperature oxidation properties (increase with laser density at 330J/m) of Inconel 718 fabricated by SLM. But there is no consistent variation of mechanical properties of Inconel 718 parts studied by K.N. Amato, et al., [38] fabricated in argon and nitrogen atmosphere using SLM process. SLM components properties are below or near the properties of LMD parts.

Manufacturing of almost 100% dense parts, repairing complex components used in automotive, aerospace, defense, injection mold cores, mold cavities and conformal cooling channels is possible with Beam Deposition (BD) process. This process is used for fabrication of nuclear and chemical industrial parts, Functionally Graded Materials (FGM) and Functionally Graded Composites. The various researches carried out for processing of metal powders by different BD processes is given in the Table VI and some similar type of summary of research was done by Shahmeer Baweja, et al., [39] on Direct Metal Deposition is also available. William E. Frazier [40] studied the PBF and BD process qualifications, process controls (real time and closed loop). The SLS require low energy consumption, and low impact on environment. Whereas the BD method repairs complex parts at low cost and thereby saving economy.

Table- VI: The details of researches carried out on different Beam Deposition (BD) processes

S. No.	Type of Process	Type of Metal Powders	Type of Machine used	Summary of Research	Applications	Ref. No.
1	DED	Ti-6Al-4V	Optomec LENS MR-7 System	Microstructure model has been developed by Kelly and Charles which calculates the phase fraction, morphology, and alpha lath width	The present technique can used in any LENS processes for repeatative heating	[41]
2	LMD	IN625 (gas atomized spherical particles size 15-45µm), MicroTiC (particles size 2-5µm) and nanoTiC (particles size 40nm)	LMD	Addition of micro TiC in Inconel 625 promotes columnar dendrites which are relatively coarsened. But nanoTiC improves microhardness, tensile strength and wear resistance	The parts produced used in aerospace and defense	[42]

3	LENS	Ti-xV and Ti-xMo	Optomec LENS	The micro hardness of functionally graded samples was increased up to 12% addition of vanadium and 10% addition of molybdenum to the titanium	These FGM`s used in structural and biomedical applications	[43]
4	LENS	IN718, IN625, IN690,SS316,SS304, Ti-6Al-4V, NdFeB (particles size 40-180µm)	Optomec LENS	Direct metal deposition is undergoing a rapid advancement	For production of fully dense parts	[44]
5	LENS	SS316	Optomec LENS	Fabrication of quality complex metal parts and tooling directly from 3D CAD data	Fabrication of dense injection mold cores, mold cavities and conformal cooling channels	[45]
6	LENS	H13, SS316 (both powder particles size -80 ±325 mesh)	Optomec LENS	Fully dense SS316 parts with powder particles size -325mesh were high strength than H13 parts	Accurate production of dense injection mold cores and mold cavities	[46]
7	LENS	SS316, H13	Optomec LENS	The molten zone length from 0.5 to 1.5mm formed at solid-liquid interface cooling temperature from 200-600K/s	----------------	[47]
8	LENS	Stainless steel, Ni-alloys, Ti-alloys, Co.	Optomec LENS	This process used for repairing of complex parts which are considered previously non repairable	Repairs of aerospace and defense components, gas turbine blades, drive shafts, drive and couplers	[48]
9	LENS and EBM	Ti-6Al-4V	Optomec LENS and Arcam AB EBM	Microstructures of all LENS and EBM parts showed directional columnar; LENS parts showed better low cycle fatigue performance and EBM parts high tensile strength	Production of mechanical components subjected to tensile force and fatigue	[49]
10	LMD	V, Cr, Fe, SS316 and Ti-6Al-4V substrate	LMD	A transition route was introduced to prevent intermetallic phases (like TiFe, $TiFe_2$,TiCr which are brittle) between Ti-6Al-4V and SS316	Production of aerospace bodies instead of Al alloys; Nuclear and chemical industrial applications	[50]
11	DMD	IN625 (particles size distribution 45-135µm)	POM's DMD	Microstructures of as deposited parts observed by SEM were most consist of columnar dendrites which are epitaxial from substrate	Production of directionally solidified components and repairs on costly complex parts	[51]
12	DED	Ti-6Al-4V	DED	Prior-β grains (long & thin) grown along the built direction resulted in anisotropic tensile elongation, and ductility is more along transverse direction than the longitudinal direction	Properties of additive manufactured Ti-6Al-4V parts were similar to wrought Ti-6Al-4V parts.	[52]
13	Laser AM (LAM)	Ti-6Al-2Zr-2Sn-3Mo-1.5Cr-2Nb Titanium alloy	LAM machine	For slow scanning velocity equiaxed grain solidified microstructure was obtained. High powder fed rate leads to heterogeneous nucleus	For cladding process	[53]
14	LENS	SS316, IN690, MM10	Optomec LENS	A new powder feeder design that controls the powder flow rate for producing dense graded parts or layered structures	Automotive and chemical containers	[54]
15	LENS	Mo-Si-B; Nb-Si (particles size distribution -60 to +335µm)	Optomec LENS	Two different alloys of Mo with 10%B and Nb with 35%Si were deposited and silicides formed	Structural silicide(Mo-Si-B; Nb-Si; $NbSi_2$; Nb_5Si_3; Nb_3Si) materials used for high temperature applications	[55]
16	LENS	SS316, IN625	Optomec LENS	Fabrication of fully dense near net shaped complex parts from a CAD solid model was demonstrated	----------------	[56]
17	LENS	SS316, SS304L, IN625, IN690 (particles size distribution -60 to +335µm)	Optomec LENS	To understanding LENS process for determining micro(melt pool) and macro(part) thermal history, visible & thermocouple techniques are used	Production of automotive, aerospace and nuclear power plant components	[57]
18	LENS	H13, M300	Optomec LENS	Critical issue was characterization of powder flow control system to develop the laser deposited composite and FGM structures	Production of aerospace and defense parts	[58]
19	LENS	Ti-10%Cr; Ti-10% Nb	Optomec LENS	Thermodynamic enthalpy of mixing of constituents for the deposition of Ti-10%Cr; Ti-10%Nb has been demonstrated	Manufacturing of complex components used in aerospace and automotive applications	[59]
20	LENS & Numerical Study	TiC, SS316L	Optomec LENS	Cooling rate in Computational simulation showed 16% error, as compared with experimental data	----------------	[60]

21	LENS	Nanoscale TiB, Ti-6Al-4V	Optomec LENS	Boride reinforcements in a titanium base matrix have been deposited and forming metal matrix composites	For TiB reinforced Ti metal-matrix composite Parts production	[61]
22	LADMD	SS316, IN625, Ti-6Al-4V	POM's DMD	This research describe the development and commercialization of LADMD Technology	----------------	[62]
23	DLD	SS316L (particles size 54-150µm)	DLD	Parts produced by pulse frequency are smoother than constant frequency using DLD process	For Functional prototyping and tooling applications	[63]
24	Lasforming	Ti-6Al-4V	Aeromet's Lasforming machine	Microstructure of the layer band consist of larger colonies of acicular α outline in transformed β phase	Fabrication of dense parts	[64]
25	LENS	TiO_2 ceramic powder on Ti substrate	Optomec LENS	Graded TiO_2 ceramic addition on porous Ti substrate greatly increase the hardness and surface wettability	Load bearing implants such as total hip prostheses	[65]
26	LENS	Ti, Ti-6Al-4V, Co-Cr-Mo, NiTi	Optomec LENS	Fabrication of porous and functionally graded load bearing implants for increasing its vivo life time	Load bearing implants	[66]
27	LENS	TiC, Ti	Optomec LENS 750 system	With the change in composition from pure Ti(>99.6% purity) to approximately 95 Vol% TiC (99.9% purity), a crack free functionally graded TiC/Ti composite was manufactured	Fabrication of functionally graded composites	[67]
28	DED	UNS N06625	IREPA CLAD System	Martensitic SS UNS G41400, UNS S41000, precipitation-hardened martensitic SS UNS S17400, and super-duplex SS UNS S32750 substrates have UNS N06625 powder deposition. These substrates showed good performance used in oil fields	Production of oil field ferrous parts	[68]
29	DMD	Ti 99.76 wt% (TiGd2 grade) and 99 wt% Al grade	HAAS 2006D with 5 axes table	Physical properties & cracks formation of the FGS and FGM in the Ti-Al alloy system was controlled	Production FGS & FGM using Ti-Al alloy	[69]
30	DMD	SS316L, Colmonoy6, Stellite6, SS420, Tool steel	POM's DMD 505	FGMs & wafer-layered parts consist of two different metal alloys have different tensile strength and also fractures than that of individual constituent alloy	Production of FGMs and Wafer-layered structures	[70]
31	LENS	SS316L	Optomec LENS MR-7	LENS is an effective technique for the fabrication of fully dense cubic samples using SS316L	Production of corrosion resistance, crack free full density parts	[71]
32	DMD	H13 Tool steel, SS41C	POM's DMD 505	Bond strength is higher in the directly clad H13 tool steel than H13 tool steel clad with SS41C as buffer layer. Bonding at the interface is free from cracks & pores	Manufacturing of bimetallic structures	[72]
33	DMD	SS316L Powder and SS316L Wire	POM's DMD	A simultaneous feeding of wire from a lateral nozzle & powder particles from coaxial nozzle into the melt pool for parts fabrication	Production of multilayer parts	[73]

IV.METALLURGICAL MECHANISMS

A.Molten Pool Behavior

The part properties are controlled from point to point by adding various alloy powders in varying amount during in the BD process [74]. Initially in laser metal deposition process, laser beam generates mobile melt pool area on metal substrate into which continuously, and precisely controlled metal powder is injected. Fig. 5a shows a single line SS316 the molten pool with a clear contour [20], [57], [58]. In this small heat effected zone molten pool can be dimensionally steady having uninterrupted solidification. Fig. 5b showed molten pool size and its morphology by real time thermal imaging used as a feeds back for controlling temperature gradient, and cooling rate of LMD process [20], [47], [57]. Based on modeling and experimentations the effects of laser processing parameters such as laser power and scan speed on the molten pool behavior was studied. Molten pool geometry depends on distribution of heat input for a constant scanning speed. The Predefined range melt pool size is adjusted by the laser power. So, initially the cooling of the melt pool is due to conduction of heat through the part and substrate. Cooling rates at solid-liquid interface are varied from 103K/s-104K/s based on substrate temperature and laser energy heat input. Hence, desired microstructures and properties of LMD components are controlled [15]. Laser metal deposits on substrate are bonded metallurgically, but not mechanically.

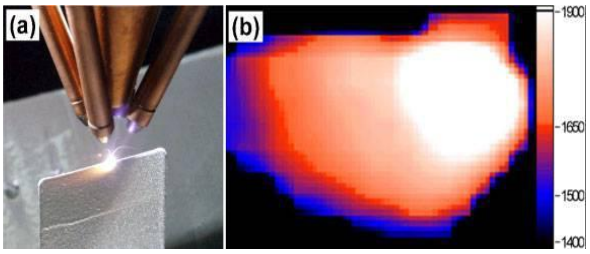

Fig. 5. (a) A single line LMD part and (b) molten pool viewed from side showed temperature in kelvin [20].

An experiment conducted by Jingjing Yang, et al., [75] proposed that the increasing of scan velocity from 600 to 1000mm/s the martensite size first increases and then decreases.

So martensite size can be controlled by varying hatch spacing and scan velocity of SLM processed Ti-6Al-4V [76], and in LENS processed SS304L single phase austenite structures were produced directly from solidification and in another way ferrite was transformed to austenite this was studied by John A. Brooks, et al., [77]. The phase transformation and melt pool size in laser melting (LM), LENS or any other metal additive manufacturing processes can be controlled by varying scan speed, laser power, and hatch spacing.

B. Thermal History

The complex thermal histories occurred at various locations of deposited parts due to layer by layer manufacturing of LMD. The LMD thermal histories are generally due to melting and reheating cycles at relatively low temperature. So complex thermal behavior in LMD/LMD promotes complex microstructures and phase transformations [20], [51], [57]. A very small focused laser beam can form a rapidly movable melt pool which result in high solidification rate and melting instability. Because of varying thermal gradient present during solidification of the part, it tends to the accumulation of complicated residual stresses. These stresses leads to deformation, and cracks formation in LMD processed components made of nickel based alloys, titanium alloys, steels, and other special materials. The two major problems in the LMD are residual stresses formation and microstructures uncontrolled. So, an in depth knowledge in the process and evaluation microstructure are required based on scan speed, temperature & distribution history of powder composition.

V. MICROSTRUCTURAL PROPERTIES

A. Surface Roughness

Powder bed fusion process is used for producing small components with good surface finish. Whereas the parts produced by LMD/DMD coaxial powder feeding system have high surface roughness, because of the presence of bigger melt pool induced by bigger size diameter beam and more metal powder deposition. DMD parts have higher surface roughness on the top surface than its side walls. Power of laser, scanning speed and powder feeding rate are three main parameters affecting the roughness of DMD/LMD parts [20], [74]. The roughness in general, is directly proportional to the deposited layer thickness. The reduction of scan speed can decrease the wall roughness.

B. Grain Size and Microstructure

The mechanical properties of AM processed parts depend on the solidification microstructure. Layer based additive manufacturing requires heating and cooling at high rates (10^3-10^8 K/s) at solid-liquid interface in a very small size molten pool (~1mm). A directional cellular microstructure of laser sintering (LS) and LMD proceed 316L powder and LM processed Fe-Ni-Cu-FeP are presented. The grain size at the bottom of the part is 4.20-4.8µm and at top is an average of 5.5µm. The grains are coarsened and equiaxed during high material deposition or high layer thickness at high laser power. But it was observed columnar grains at low laser power [20]. The columnar dendrites were form due to the addition of TiC into the IN625, when processed by LMD [42]. The LENS processed SS316L and H13 melt pool size varies from 0.5mm-1.5mm [47]. The directional columnar grains of Ti-6Al-4V processed by LENS and EBM were obtained [49]. The microstructures of IN625 parts produced by DMD have columnar dendrites which are epitaxial in shape appearing from substrate [51]. Visible and thermocouple techniques were used to determine micro (melt pool) and macro (part) thermal history to understand the microstructure of LENS processed components [57]. The large colonies of acicular α outline in transformed β phase in Ti-6Al-4V lasforming parts were obtained [64]. The thermal behavior of DED and SLM processed parts have acicular α′ martensitic microstructure, high tensile and yield stresses while the EBM processed parts are free from residual stresses with an α+β lamellar microstructure [23].

VI. APPLICATIONS OF BD PROCESS

A. Repairs and Remanufacturing

Aerospace components often have complex geometries and high buy-to-fly ratios (i.e. the ratio of weight of raw material to the final part weight) are manufactured by LENS/DMD. These processes use advanced materials, such as titanium

-alloys, nickel based super alloys, special steels, or ultrahigh-temperature ceramics for achieving desired properties. The utilization of LENS/DMD in the aerospace industries is not limited to produce new parts, but this is extended to repair aircraft engine parts such as gas turbine blisks [23], and gas turbine blades as shown in Fig. 6. Such that it is reducing the cost and extending longer wear life than new parts. A blisk is a turbo-machine component comprising both disk and blades [15]. Another feasible application of LMD/DMD is the repairs of drive shafts, bearings, seals, and coupler surfaces on shafts, which are typically considered non repairable by conventional welding techniques [20].

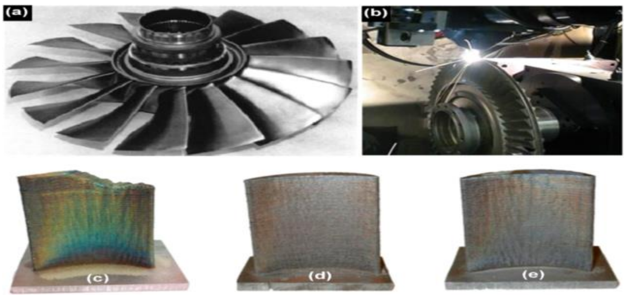

Fig. 6. Damaged blisk repaired using directed energy deposition process: (a) repaired blisk, (b) repairing in process; damaged turbine blisk repaired with directed energy deposition; (c) damaged blade, (d) original undamaged blade, (e) repaired bladed [23].

B. Cladding and Hardfacing

Cladding and hardfacing are form of repairs build-up applied to deposit new layers of powder material on a substrate. Multiple layers can be deposited to form complex shapes.

These two are used for material surface property modification and manufacturing of multilayer coatings by LMD/DMD. POM Group Inc. has developed large DMD machines (DMD 105D) for hardfacing and repair/cladding of large dies, molds and any parts [15], [20]. AM processed Ti-6Al-2Zr-2Sn-3Mo-1.5Cr-2Nb alloy was a type of cladding part [53].

C. Designed Materials

There is continuous material development of functionally gradient materials (FGM's) from Bronze Age to present. Two different criteria's used to classify functionally graded materials are based on structure of materials and based on size [15], [32]. FGM's can be further divided into two main groups based on structure of materials are continuously and discontinuously structured. In continuous FGM, there is the continuous gradient present from materials to materials. But in discontinuous FGM's, material gradient is provided in layer by layer. Based on size of materials, FGM's are categorized into two main types. They are thin FGM's and bulk FGM's. Thin FGM's have thin sectional surface coating, but bulk FGM's have complete volume of materials. Manufacturing processes like Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD) and Self propagating High temperature Synthesis (SHS) method are used to manufacture thin FGM. Whereas, bulk FGM's are produced using powder metallurgy, centrifugal casting and solid freeform/additive manufacturing techniques [32].

In last few years, there was a growing interest in the area of functionally gradient materials (FGMs) due the properties of FGM's changes significantly and continuously from one surface to another, which result from the heterogeneous microstructure. Thus eliminating interface problems like stress concentrations and poor adhesion. It possesses a position dependent microstructure, chemical composition these can lead to the continuous variation with mechanical, electrical and thermal properties of materials. A thermal barrier of 10mm thick FGM withstand at a surface temperature of 17000 ^{0}C and at a temperature gradient of 10000 ^{0}C for space plane was developed by Japan in 1987. The various fields of applications of FGM's are aerospace and aeronautics, thermal barrier coatings, chemical plants, electronics, energy conversion, commodities, biomaterials (i.e. artificial bones, teeth), optics, MEMS and sensors, functionally graded piezoelectric materials and shape memory alloys [54], [78].

When combinations of two extreme properties are required in a part, such as toughness and hardness, thermal resistance and anti-oxidation properties at high temperature side, toughness and mechanical strength at low temperature side then FGMs are used. The typical applications of FGMs are cutting tools and machine parts subjected to mechanical shock, heat, wear, and corrosion resistance. Fig. 7a shows composite and FGM cutting tools. Composite tool made from metal to ceramic accumulate residual stresses and tool failure when it experiences work piece. But in case of FGM cutting tool, where FGM materials used in between metal and ceramic increases thermal strength and life of the tool. Fig. 7b shows FGM turbine blade, its thermal conductivity and mechanical strength are continuously vary from metal to ceramic region [32].

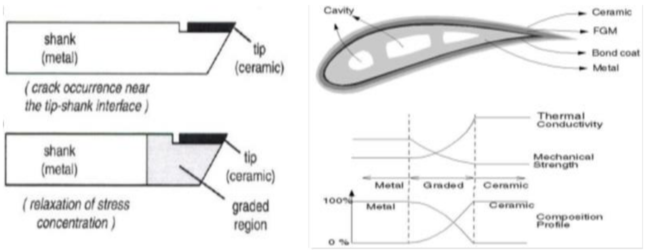

Fig. 7. (a) Conventional and FGM metal cutting tools, (b) Turbine blade material containing FGM [32].

A new methodology for design, representation and fabrication of performance based designed materials was developed by Mazumder's group using DMD. Heterogeneous objects are classified into multi-material objects, and functionally graded materials. These new classes of composite materials possess continuous variation material properties along the geometric profile [15], [20]. Collins et al., [43] studied the deposition of Ti-xVo compositionally graded binary alloys, from Ti to Ti-25 at-%V, for a 25mm length and 10mm diameter specimen by laser metal deposition process. Intersecting microstructure gradients are tailored across the alloy (Fig. 8). They also developed Ti-xMo compositionally graded binary alloys, from Ti to Ti-25 at-%Mo. The ability to achieve such substantial changes in microstructure of Ti to Ti-25 at-%Mo as shown in Fig. 9, across the small length, made laser metal deposition process as a highly attractive method for the development of novel structured functionally gradient material parts with unique properties.

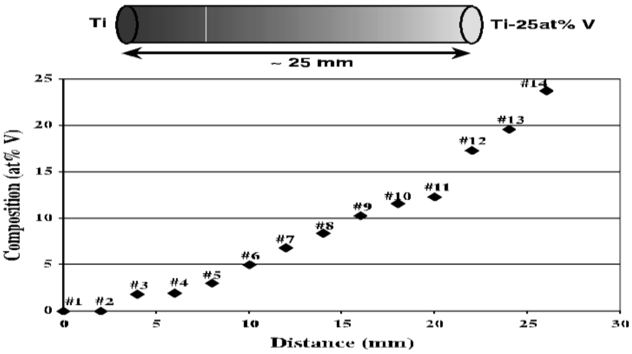

Fig. 8. Composition profile across the Ti-xV graded alloy deposited by LENS [43].

Design and fabrication system for heterogeneous components are integrated, especially for FGMs and a research work on homogenization process using a mixture of Nickel and Chromium are disclosed. A structure designed by homogenization design method (HDM) and manufactured by direct metal deposition showed negative thermal expansion of dL/L≈0.00065mm from 150 ^{0}C-300 ^{0}C [20]. FGMs have to show good performance and reliability for a particular application.

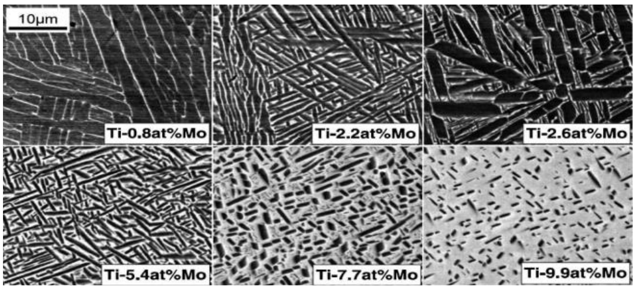

Fig. 9. Microstructures of Ti-xMo graded alloy with increasing Mo contents [20], [43].

VII. NEW DEVELOPMENS AND PROSPECTS

A. Functionally Gradient Materials

FGM's properties continuously vary in the direction of thickness. But there is a huge demand for FGM's in modern applications due to varying properties of materials in both thickness and axial directions. Recently, a gradient material having with varying of properties in both directions were also manufactured using LMD process. Such type of gradient smart materials is known as bidirectional functionally gradient (BDFGMs) materials [32]. Even though, the BD machines available for the production of FGM's, few critical issues are not solved. Such as unavailability of suitable database for FGM's in terms of design, process parameters & testing, which are not suitable for mass production, complex parts cannot be manufactured due to high cost are the future challenges in this BD processing field. There is a big challenge for getting mechanical properties of AM parts to those of conventional processed parts.

B. Hybrid Manufacturing Process

The problems encountered in metallic wire feedstock BD process are overcome by hybrid manufacturing process. This process produces internal and the overhanging features of complex parts. These components have very rough surface and dimensional inaccuracy. This can be possible to overcome these issues by combining or to hybridizing two or more processes in one machine tool named as "Workstations for Hybrid Additive and Subtractive Processing" (WHASPS). These machines were introduced in the market for combing AM process and subtractive process, such as grinding, Lathe operations, drilling, and milling operations [73]. It can manufacture aerospace parts and also repair high-value parts at less material wastage associated with buy-to-fly ratio [15]. This WHASPS is also known as hybrid RP machine [79].

A hybrid RP machine developed for an additive process called 3D welding and milling for increasing accuracy and surface roughness. In this process it uses AWS 5.18 E70S-6 mild steel wire of 0.9 mm diameter [79]. DED process uses also metal wire feedstock instead of alloy powders. An AISI1010 steel foil of 150μm thick used to weld complex parts by DED process for obtaining high hardness and strength [80]. The processing parameters affect the track uniformity, surface quality, interface between the substrate and H11 steel stock produced by LMD [81].

LMD is not permitted to use metal foils, but also allows the use of the glass wire filaments as feedstock for producing transparent soda-lime glass [82]. The laser cutting machine was converted into DMD machine by Jayanth N, et al., in such a way that it will perform direct metal deposition. The nozzle is modified and yet to modify powder feeder suitable for Laser Based Direct Metal Deposition (LBDMD) process [83]. The current process is semi-automatic, but it needs to automate the process for reducing errors and time consumption. The future work will be the fabrication of components with different metal alloy powders which are processed by plasma rotating electrode process (PREP) or gas-atomization (GA). The PREP powders do not have pores. So properties of PREP Ti6Al4V powder parts are better than GA powder parts [84]. Hence it is a challenge for production all types of alloy powders by PREP at efficient cost suitable for BD processes.

C. 4D Printing Technology

There is an emerging trend in the new technology spectrum. That is the introduction of time as the fourth dimension, which can combine with 3D printing and form the 4D printing [85]. The consideration of time in the 3D printing is not about how much time required to printed parts, but also how those parts can change their shapes over a period of time, based on properties of materials. This 4D printing has developed by Stratasys Education and its R&D departments in collaboration with Massachusetts Institute of Technology's self-assembly laboratory.

Normally Shape-memory materials (SMMs) are 4D printing materials. These materials possess unique property of remembering their original shapes when they return from various locations. Shape-memory materials include shape-memory polymers (SMPs), shape-memory alloys (SMAs), ferromagnetic SMAs (FSMAs). Selection of materials, technology and design, are the challenges in the 4D printing research area.

VIII. CONCLUSIONS

Additive manufacturing technology is a more than 30 years old technology and has started to enter into the mature growth stage. It is also called as Rapid Prototyping or Rapid Manufacturing. Now, the AM technology became competitive with traditional methods of manufacturing in terms of speed, cost, accuracy and reliability. It can produce parts in few hours that depending on the complexity of components, size of the component, and type of machine being used. Even though certain metallic powders possess excellent processability in powder metallurgy routes are found not applicable in some additive manufacturing processes. So a proper database for metal AM to be developed.

In this review article, the research work done on various powder blown Beam Deposition(BD) processes like LENS, LMD, DED, and DMD have been presented. It is widely focused on manufacturing of fully dense components, functionally graded materials (FGM's) applicable to aeronautics, automotive, defense and chemical reactor using different alloy powder particles.

Melt pool and thermal behavior, mechanical properties such as UTS, YS, hardness, elongation and microstructural properties of BD parts are discussed.

This paper provides information about AM standards, present scenario of metal AM, porous bio-implants, FGM mechanical parts and tooling, repairs and coating of parts, hybrid manufacturing, 4D printing and current challenges in additive manufacturing.

ACKNOWLEDGMENTS

One of the Authors (D. Dev Singh) would like to express thanks to Management and Principal of CMR institute of Technology for their continuous support and encouragement during this work.

REFERENCES

1. M. D. Monzon, Z. Ortega, A. Martínez, and F.Ortegaet, “Standardization in additive manufacturing: activities carried out by international organizations and projects,” The Int J of Adv Manuf Technol., Vol. 76, Sept.2015, pp. 1111-1121.
2. Patri K. Venuvinod, Wei Yin Ma, “Rapid Prototyping: Laser-based and Other Technologies,” New York, Kluwer Academic Publishers, 1st edition, 2004.
3. Farooq I Azam, Ahmad Majdi Abdul Rani, Khurram Altaf, T.V.V.L.N Rao, and Haizum Aimi Zaharin, “An In-Depth Review on Direct Additive Manufacturing of Metals,” ICMMPE 2017, November 22-23, 2017. Parkroyal Penang, Malaysia. IOP Conf Series: Mater Sci Eng., Vol.328, 2018, pp.1-8.
4. Jan Burch, What Is the Difference Between a Prototype & a Model? http://yourbusines.azceral.com/diference-between-prototype-model-28781.html, May 11, 2018.
5. http://engineeringpsycho.blogspot.com/2014/09/diference-between-model-and-prototype.html.
6. Chua C.K, and Leong K.F, Lim C.S “Rapid Prototyping: Principles and Application,” Singapore, World Scientific Publishing Co. Pvt. Ltd, 2nd edition, 2003.
7. https://www.twi-global.com/technival-knowledge/faqs/fa-what-is-virtual-prototyping.
8. https://www.tth.com/diference-between-3d-printing-additive-manufacturing-rapid-prototyping.
9. Yuweizhai, Diana A. Lados, and Jane L. Lagoy, “Additive Manufacturing: Making Imagination the Major Limitation,” JOM, Vol.66, March 2014, pp. 808-816.
10. Prajakta Subhedar, “Additive Manufacturing: A next gen fabrication,” Int J of Current Eng Technol., Vol. 8, Feb.2018, pp. 75-78.
11. Duyao Zhang, Shoujin Sun, Dong Qiu, Mark A. Gibson, Matthew S. Dargusch, Milan Brandt, and et al., “Metal Alloys for Fusion-Based Additive Manufacturing,” Adv Eng Mater., Vol. 20, 2018, pp. 1700952(1-20)
12. Siddharth Jeet, Abhishek Barua, and Sasmita Kar, “Free-Form Fabrication-An Emerging Trend in Engineering,” Seventh Intl Conference on Advances in Robotic, Mechanical Engineering and Design-ARMED-2018, Apr 27-28, 2018, Odisha, India, Grenze Scientific Society, May 2018, pp. 78-84.
13. Y. Kok, X.P. Tan, P.Wang, M.L.S. Nai, N.H. Loh, E. Liu, and et al., “Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review,” Mater Design, Vol. 139, 2018, pp. 565-586.
14. Dhanesh Avinash Dhanawade, and Bhatwadekar S.G, “A Review on Types of Powder Bed Fusion Process in Additive Manufacturing Technology,” Int J of Eng Technol Sci and Res, Vol. 4, Nov. 2017, pp. 991-995.
15. Insaf Bahnini, Mickael Rivette, Ahmed Rechia, Ali Siadat, and Abdelilah Elmesbahi, “Additive manufacturing technology: the status, applications, and prospects,” The Int J of Adv Manuf Technol, Vol. 97, March 2018, pp. 147-161.
16. Panagiotis Stavropoulos, and Panagis Foteinopoulos, “Modelling of additive manufacturing processes: a review and classification,” Manuf Rev, Vol. 5, 2018, pp. 1-26.
17. E. Herderick, “Additive Manufacturing of Metals: A Review,” Materials Science and Technology (MS&T) 2011, Columbus, Ohio. ASM International (176252), October 16-20, 2011, pp.1413-1425.
18. A Zadi-Maad, R Rohib, and A Irawan, “Additive manufacturing for steels: a review,” Mineral Processing and Technology International Conference 2017 IOP Publishing, IOP Conf. Series: Mater Sci Eng, Vol. 285, 2017, pp. 1-8.
19. Thomas Duda and L. Venkat Raghavan, “3D metal printing technology: the need to re-invent design practice,” AI & Soc, Vol. 33, Feb. 2018, *pp. 241-252*.
20. D. D. Gu, W. Meiners, K. Wissenbach, and R. Poprawe, “Laser additive manufacturing of metallic components: materials, processes and mechanisms,” Int Mater Rev, Vol. 57, 2012, pp. 133-164.
21. Kamran Shah, “Laser Direct Metal Deposition of Dissimilar and Functionally Graded Alloys,” Ph.D. Thesis, Faculty of Engineering and Physical Sciences, The University of Manchester 2011.
22. D T Pham, S Dimov, and F Lacan, “Selective laser sintering: applications and technological capabilities,” Proc of the Inst of Mech Eng Part B: J Eng Manuf, Vol. 213, 1999, pp. 435-449.
23. Shunyu Liu, and Yung C. Shin, “Additive manufacturing of Ti6Al4V alloy: A review,” Materials & Design, Vol. 164, Dec. 2019, pp. 107552(1-23).
24. A. Simchi, “Densification and Microstructural Evolution during Co-sintering of Ni-Base Superalloy Powders,” Metall Mater Trans A, Vol. 37A, Aug. 2006, pp. 2549-2557.
25. Leila Ladani, Jafar Razmi, and Soud Farhan Choudhury, “Mechanical Anisotropy and Strain Rate Dependency Behavior of Ti6Al4V Produced Using E-Beam Additive Fabrication,” J Eng Mater Technol, Vol. 136, July 2014, pp. 031006(1-7).
26. Raya Mertens, Stijn Clijsters, Karolien Kempen, and Jean-Pierre Kruth, “Optimization of Scan Strategies in Selective Laser Melting of Aluminum Parts With Downfacing Areas,” J Manuf Sci Eng, Vol. 136, Dec. 2014, pp. 061012(1-7).
27. Nesma T. Aboulkhair, Nicola M. Everitt, Ian Ashcroft, and Chris Tuck, “Reducing porosity in AlSi10Mg parts processed by selective laser melting,” Additive Manufacturing, Vol. 1-4, Aug. 2014, pp. 77-86.
28. Xuesong Han, Haihong Zhu, Xiaojia Nie, Guoqing Wang, and Xiaoyan Zeng, “Investigation on Selective Laser Melting AlSi10Mg Cellular Lattice Strut: Molten Pool Morphology, Surface Roughness and Dimensional Accuracy,” Materials (Basel), Vol. 11, March 2018, pp. 392(1-23).
29. Omar O. Salman, Alexander Funk, Anja Waske, Jürgen Eckert, and Sergio Scudin, “Additive Manufacturing of a 316L Steel Matrix Composite Reinforced with CeO_2 Particles: Process Optimization by Adjusting the Laser Scanning Speed,” Technologies, Vol. 6, Feb. 2018, pp. 25(1-10).
30. Kaufui V. Wong, and Aldo Hernandez, “A Review of Additive Manufacturing,” ISRN Mechanical Engineering, 2012, pp. 208760(1-10).
31. P. Chandramohan, Shepherd Bhero, K. Manikandasubramanian, and B.Ravishankar, “A Review of Additive Manufacturing of α-β Ti alloy Components through Selective Laser Melting and Laser Metal Deposition,” J Eng Sci Technol., Vol. 13, 2018, pp.790-812.
32. Valmik Bhavar, Prakash Kattire, Sandeep Thakare, Sachin patil and Dr.RKP Singh, “A Review on Functionally Gradient Materials (FGMs) and Their Applications,” AMRMT 2017, IOP Conf. Series: Mater Sci Eng. Vol. 229, 2017, pp. 012021(1-10).
33. B. Kieback, A. Neubrand, and H. Riedel, “Processing Techniques for Functionally Graded Materials,” Mater Sci Eng A, Vol. 362, Feb. 2003, pp. 81-105.
34. Subodh Kumar, Ajit Kumar Singh Choudhary, Jamshed Anwar, and Vinay Sharma, “Optimization of Process Parameters in Direct Metal Deposition Technique Using Taguchi Method,” Int J of Mech Eng Technol, Vol. 7, May-June 2016, pp. 225-239.
35. H.M. Gajera, and Dr. K.G.Dave, “A review: Challenges stand off for tooling material in AM field,” Int J Adv Eng Res Dev, Vol. 4, Nov. 2017, pp.854-856.
36. Chetankumar M. Patel, Sandip. B.Patel, and MitK.Shah, “Experimental Investigation of Mechanical Properties and Surface Roughness of CL50WS Material Parts Made by Selective Laser Sintering Process,” Int J for Sci Res Dev, Vol. 3, 2015, pp.306-310.
37. Qingbo Jia, and Dongdong Gu, “Selective laser melting additive manufacturing of Inconel 718 super alloy parts: Densification, microstructure and properties,” J Alloy Compd, Vol. 585, Oct. 2014, pp. 713-721.
38. K.N. Amato, S.M. Gaytan, L.E. Murr, E. Martinez, P.W. Shindo, J. Hernandez, and et al., “Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting,” Acta Mater, Vol. 60, March 2012, pp.2229-2239.
39. Shahmeer Baweja, and Ali Kamrani, “Direct Metal Deposition: Survey,” University of Houston, Houston, TX, 77407, USA, 2016, pp.1-74.

40. William E. Frazier, “Metal Additive Manufacturing: A Review,” J Mater Eng Perform, Vol. 23, June 2014, pp.1917-1928.
41. Jeff Irwin, Edward W. Reutzel, Pan Michaleris, Jay Keist, and Abdalla R. Nassar, “Predicting Microstructure from thermal history during Additive Manufacturing for Ti-6Al-4V,” J of Manuf Sci Eng, Vol. 138, Nov.2016, pp. 111007(1-11).
42. Dongdong Gu, Sainan Cao, and Kaijie Lin, “Laser Metal Deposition Additive Manufacturing of TiC Reinforced Inconel 625 Composites: Influence of the Additive TiC Particle and Its Starting Size,” J Manuf Sci Eng, Vol. 139, Nov. 2017, pp. 041014(1-13).
43. P.C. Collins, R. Banerjee, S. Banerjee, and H.L. Fraser, “Laser deposition of compositionally graded titanium-vanadium and Titanium-molybdenum alloys,” Mater Sci Eng A, Vol. 352, 2003, pp.118-128.
44. Eric Schlienger, Duane Dimos, Michelle Griffith, Joseph Michael, Mike Olive, Tony Romero, and et al., “Near net shape production of metal components using LENS,” Sandia National Laboratories, SAND98-0664C, OSTI, March 1998, pp.1-8
45. Clint Atwood, Michelle Griffith, Lane Harwell, Eric Schlienger, Mark Ensz, John Smugeresky, and et al., “Laser Engineered Net Shaping (LENS): A tool for direct fabrication of metal parts,” Sandia National Laboratories, SAND98-2473C, OSTI, March 1998, pp. 1-9
46. M. L. Griffith, D. M. Keicher, C. L. Atwood, J.A. Romero, J. E. Smugeresky, L.D.Harwell and et al., “Free Form Fabrication of Metallic Components Using Laser Engineered Net Shaping (LENS™),” Sandia National Laboratories, U.S. Department of Energy Grant No.DE-AC04-94AL85000, pp.125-131.
47. William Hofmeister, Michelle Griffith, Mark Ensz, and John Smugeresky, “Solidification in Direct Metal Deposition by LENS Processing,” JOM, Vol. 53, Sept. 2001, pp. 30-34.
48. Robert P. Mudge, and Nicholas R. Wald, “Laser Engineered Net Shaping Advances Additive Manufacturing and Repair,” Welding Journal, Vol. 86, Jan. 2007, pp.44-48.
49. YuweiZhai, Haize Galarraga, and Diana A. Lados, “Microstructure Evolution, Tensile Properties, and Fatigue Damage Mechanisms in Ti-6Al-4V Alloys Fabricated by Two Additive Manufacturing Techniques,” Procedia Engineering, Vol. 114, 2015, pp.658-666.
50. Wei Li, Sreekar Karnati, Caitlin Kriewall, Frank Liou, J. Newkirk,Karen M. Brown Taminger and et al. “Fabrication and characterization of a functionally graded material from Ti-6Al-4V to SS316 by laser metal deposition,” Additive Manufacturing, Vol. 14, Feb. 2017, pp. 95-104.
51. G.P. Dinda, A.K. Dasgupta, and J. Mazumder, “Laser aided direct metal deposition of Inconel 625 superalloy: Microstructural evolution and thermal stability,” Mater Science and Engineering A, Vol. 509, Jan. 2009, pp.98-104.
52. Beth E. Carroll, Todd A. Palmer, and Allison M. Beese, “Anisotropic Tensile Behavior of Ti-6Al-4V Components Fabricated with Directed Energy Deposition Additive Manufacturing,” Acta Materialia, Vol. 87, Jan. 2015, pp. 309-320.
53. Qiang Zhang, jing Chen, Lilin Wang, Hua Tan, Xin Lin, and Weidong Huang, “Solidification Microstructure of Laser Additive Manufactured Ti-6Al-2Zr-2Sn-3Mo-1.5Cr-2Nb Titanium Alloy,” J Mater Sci Technol, Vol. 32, Sept. 2016, pp. 381-386.
54. Michelle L. Griffith, Lane D. Harwell, J. Tony Romero, Eric Schlienger, Clint L. Atwood, and John E. Smugeresky, “Multi-Material Processing by LENS,” Sandia National Laboratories, U.S. Department of Energy Grant No.DE-AC04-94AL85000, pp. 387-393.
55. C. A. Brice, K. I. Schwendner, S. Amancherla, H. L. Fraser, and X. D. Zhang, “Characterization of Laser Deposited Niobium and Molybdenum Silicides,” Materials Research Society Symposium Proceedings, April 24-26, 2000, San Francisco, California: Materials Research Society, Vol. 625, April 2000, pp. 31-35.
56. J.E.Smugeresky, D.M.Keicher, J.A.Romero, M.L.Griffith and L.D. Harwell, “Using the Laser Engineered Net Shaping (LENS) Process to Produce Complex Components from a CAD Model,” Proc of the international society for Optical Engineering, Lasers as Tools for Manufacturing II. SAN 97-8546, California: National Technical Information Service, August 1997, pp. 1-12.
57. M. L. Griffith, M. T. Ensz, J. D. Puskar, C. V. Robino, J. A. Brooks, J. A. Phillibe, and et al., “Understanding the Microstructure and Properties of Components Fabricated by Laser Engineered Net Shaping (LENS),” Materials Research Society Symposium Proceedings, April 24-26, 2000, San Francisco, California: Mater Res Soc, Vol. 625, April 2000, pp. 9-20.
58. Mark T. Ensz, Michelle L. Griffith, and Daryl E. Reckaway, “Critical Issues for Functionally Graded Material Deposition by Laser Engineered Net Shaping (LENS),” Sandia National Laboratories, U.S.Department of Energy Grant No.DE-AC04-94AL85000, pp. 1-8.
59. Katrin I. Schwendner, Rajarshi Banerjee, Peter C. Collins, Craig A. Brice, and Hamish L. Frase, “Direct laser deposition of alloys from elemental powder blends,” Scripta Materialia, Vol. 45, June 2001, pp. 1123-1129.
60. R.S. Amano, Z. Xu, J. Martinez Lucci, and, and Pradeep Rohatgi, “A Numerical Study of a Cooling Ratio for Laser Based Prototyping Technology with a Sample of 316L Stainless Steel,” Open Autom Contr Syst Journal, Vol. 4, May 2012, pp. 1-7.
61. R. Banerjee, A. Genc, D. Hill, P.C. Collins, and H.L. Fraser, “Nanoscale TiB precipitates in laser deposited Ti-matrix composites,” Scripta Materialia, Vol. 53, Sept. 2005, pp.1433-1437.
62. D.M. Keicher, and John E. Smugeresky, “The Laser Forming of Metallic Components Using Particulate Materials,” JOM, Vol. 49, May1997, pp.51-54.
63. Andrew J Pinkerton, and Lin Li, “An Investigation of the Effect of Pulse Frequency in Laser Multi-Layer Cladding of Stainless Steel,” Applied Surf ace Science, Vol. 208&209, 2013, pp.405-410.
64. S.M. Kelly, S.L. Kampe, and C.R. Crowe, “Microstructural Study of Laser Formed Ti-6Al-4V,” Materials Research Society Symposium Proceedings. April 24-26, 2000. San Francisco, California: Materials Research Society, Vol. 625, April 2000, pp. 3-8.
65. Vamsi Krishna Balla, Paul DuteilDeVasConCellos, WeichangXue, Susmita Bose, and Amit Bandyopadhya, “Fabrication of compositionally and structurally graded Ti-TiO$_2$ structures using laser engineered net shaping (LENS),” Acta Biomaterialia, Vol. 5, Jan. 2009, pp.1831-1837.
66. Amit Bandyopadhyay, B.V.Krishna, WeichangXue, and, Susmita Bose, “Application of Laser Engineered Net Shaping (LENS) to manufacture porous and functionally graded structures for load bearing implants,” J Mater Sci Mater Med, Vo. 20, June 2008, pp. S29-S34.
67. Weiping Liu, and J.N. DuPont, “Fabrication of functionally graded TiC/Ti composites by Laser Engineered Net Shaping,” Scripta Materialia, Vol. 48, Jan. 2003, pp.1337-1342.
68. Manuel Marya, Virendra Singh, Jean-Yves Hascoet, and Surendar Marya, “A Metallurgical Investigation of the Direct Energy Deposition Surface Repair of Ferrous Alloys,” J Mater Eng Perform, Vol. 27, Jan. 2018, pp.813-824.
69. Shishkovsky I, Missemer F, and Smurov I, “Direct metal deposition of functional graded structures in Ti-Al system,” Physics Procedia, Vol. 39, 2012, pp. 382-391.
70. Mehdi Soodi, Syed H. Masood, and Milan Brandt, “Tensile strength of functionally graded and wafer layered structures produced by direct metal deposition,” Rapid Prototyping Journal, Vol. 20, 2014, pp. 360-368.
71. Michał Ziętala, Tomasz Durejko, Marek Polański, IzabelaKunce, TomaszPłociński, WitoldZieliński, et al, “The microstructure, mechanical properties and corrosion resistance of 316L stainless steel fabricated using laser engineered net shaping,” Materials Science and Engineering A, Vol. 677, Sept. 2016, pp. 1-10.
72. M. Khalid Imran, S.H. Masood, Milan Brandt, Sudip Bhattacharya, and Jyotirmoy Mazumder, “Direct metal deposition (DMD) of H13 tool steel on copper alloy substrate: Evaluation of mechanical properties,” Mater Sci Eng A, Vol. 528, Jan. 2011, pp. 3342-3349.
73. Waheed Ul Haq Syed, Andrew J. Pinkerton, and Lin Li, “Combining wire and coaxial powder feeding in laser direct metal deposition for rapid prototyping.” Applied Surface Science, Vol. 252, Oct. 2006, pp. 4803-4808.
74. Srijan Manish, Subodh Kumar, Rakesh, and Amit Kumar Gupta, “Influence of Process Parameters on Product Characteristics in Direct Metal Deposition: A Review,” Conference Proceedings-Recent Advancements in Manufacturing and its Management-2014, February 7-8, 2014, B.I.T Sindri, Dhanbad, Jharkhand, India, Academia Publishers, Feb. 2014, pp. 1-6.
75. Jingjing Yang, Hanchen Yu, Jie Yin, Ming Gao, ZeminWang, and Xiaoyan Zeng, “Formation and control of martensite in Ti-6Al-4V alloy produced by selective laser melting,” Materials & Design, Vol. 108, June 2016, pp. 308-318.
76. Luca Facchini, Alberto Molinari, Simon Hoges, and Konrad Wissenbach, “Ductility of a Ti-6Al-4V alloy produced by selective laser melting of prealloyed powders,” Rapid Prototyping Journal, Vol.16, 2010, pp. 450-459.
77. John A. Brooks, Thomas J. Headley, and Charles V. Robino, “Microstructures of Laser Deposited 304L Austenitic Stainless Steel,” Materials Research Society Symposium Proceedings. April 24-26, 2000, San Francisco, California: Materials Research Society, Vol. 625, April 2000, pp.21-30.

78. Shailendra Kumar Bohidar, Ritesh Sharma, and Prabhat Ranjan Mishra, "Functionally Graded Materials: A Critical Review," Int J Scientific Footprints, Vol. 2, Aug. 2014, pp. 18-29.
79. Yong-Ak Song, and Sehyung Park, "Investigation into Freeform Fabrication of Multi-Material Parts by 3D Welding and Milling Process," Materials Research Society Symposium Proceedings. April 24-26, 2000. San Francisco, California: Materials Research Society, Vol. 625, April 2000, pp.37-42.
80. Chen Chen, Yiyu Shen, and Hai-Lung Tsai, "A Foil-Based Additive Manufacturing Technology for Metal Parts," J Manuf Science Eng, Vol. 139, Feb.2017, pp. 024501(1-6).
81. Stella Holzbach Oliariet, Ana Sofia Climaco Monteiro D'Oliveira, and Martin Schulz, "Additive Manufacturing of H11 with Wire-Based Laser Metal Deposition," Soldagem Insp, Vol. 22, Nov. 2017, pp. 466-479.
82. Junjie Luo, Luke J. Gilbert, Chuang Qu, Robert G. Landers, Douglas A. Bristow and Edward C. Kinzel, "Additive Manufacturing of Transparent Soda-lime Glass Using Filament-Fed Process," Journal of Manufacturing Science and Engineering, Vol. 139, June 2017, pp. 061006(1-8).
83. Jayanth N, and Ravi K R, "Modeling of Laser Based Direct Metal Deposition Process," National Conference on Technological Advancements in Engineering-2015, Sree Narayana Guru College of Engineering and Technology, Payyanur, Academia Publishers, March 2015, pp.1-6.
84. Muhammad Naveed Ahsan, "Modelling and Analysis of Laser Direct Metal Deposition of Ti-6Al-4V Alloy," Ph.D. Thesis, Faculty of Engineering and Physical Sciences, The University of Manchester 2011, pp.1-209
85. Jin Choi, O-Chang Kwon, Wonjin Jo, Heon Ju Lee, and Myoung-Woon Moo, "4D Printing Technology: A Review," 3D Printing and Additive Manufacturing, Vol. 2, 2015, pp. 159-167.

AUTHORS PROFILE

D. Dev Singh, Research scholar, Department of Mechanical Engineering, Jawaharlal Nehru Technological University Hyderabad, Telangana, India & working as Associate Professor in the Department of Mechanical Engineering, CMR Institute of Technology, Hyderabad, Telangana, India

Suresh Arjula is working as Assistant professor (Sl.G) in the Department of Mechanical Engineering, JNTUH College of Engineering Jagitial, Telangana State. He obtained Ph.D. in Mechanical Engineering from Indian Institute of Technology (IIT-BHU), Varanasi, India in 2008

A. Raji Reddy received his Ph.D. in Mechanical Engineering from Osmania University Hyderabad, in the year 2008. Presently, he is working as Director of CMR Technical Campus, Hyderabad, Telangana, India and Professor of Mechanical Engineering Department.