CHALLENGES AND RESEARCH OPPORTUNITIES IN METAL ADDITIVE MANUFACTURING

[1]BN Manjunath, [2]AR Vinod, [3]SK Verma and [4]Dr N Balashanmugam

[1,2,3,4]Central Manufacturing Technology Institute(CMTI), Tumkur road, Bengaluru
E-mail: manjunathbn.cmti@gov.in

Abstract: *Additive manufacturing has changed the way products are designed, manufactured and distributed to the consumers. It has made possible to create products previously thought too complex. Aerospace, medical, automotive and energy sectors started using additive manufacturing as they realised its potential innovation, financial and efficiency benefits. Despite the progress, there are still challenges that must be addressed, including improving the throughput, Accuracy and repeatability, surface roughness, mechanical properties, establishing standards and protocols, modelling and simulation to reduce the residual stress, certification and reducing the raw material cost. This article gives insights into the present barriers hindering the widespread adoption and research opportunities in metal additive manufacturing.*

1. INTRODUCTION

When 3D metal printing was introduced in the market during 1990’s, it was targeted for prototyping and for making models in aerospace, automobile and for custom medical devices. The name rapid prototyping was appropriate for additive manufacturing(AM) at that time. Later the advancement in AM has progressed so fast, the direction in development of AM has shifted from just making of model to making of actual part that goes into the assembly or devices. Mainly, demand from Aerospace, energy and medical industries has driven the advancement of metal AM from prototyping to production. Substantial requirements from these industries have further increased the AM technology development for many industrial applications.

The global AM market has grown by nearly five-fold over the last six years. GE’s AM group has fixed a target of selling 10,000 metal AM machines in next 10 years [1]. Material build rate in AM was less than 10cm3/hr and it is expected to go up manifold in the coming years. Imperial college, UK had forecasted that this would go up to 80 cm3/hr by the year 2023. Looking at the developments happening and the way by which majors like GE, Siemens and HP are making strong inroad into AM, it seems AM technology is waiting to explode. Industries look at AM technology from many perspectives. Firstly, they see, whether AM is a replacement for existing traditional top-down technologies. Also, they look at AM as how it could be used for refurbishing of components. Industries looks at AM on how it is going to address the quality, throughput, material integrity, cost of manufacturing and ultimately qualification of AM parts in real life applications.

Traditionally, based on the process required for making parts, machines are grouped, cellular layout is made and material is moved to various machining centres based on routing. The objective of AM is to get the parts get completed in single station. AM machine acts as a foundry and as well as part builder. It melts the powder and makes the shape of the part layer by layer. The whole concept of cellular manufacturing is taken to task, as the material need not be moved to various machines. AM machine replaces foundry, raw material cutting, turning, milling, drilling and material movement between workstations. Application of proven manufacturing concepts like Kanban would undergo a change.AM machine itself is a whole factory or an equivalent to a multitasking machine or a cell with multiple machines. There will be little need for a tool crib in an additive manufacturing environment. Stores would have fewer inventories. There may not be any in-process inventory. Coolant is not required and hence topping and refilling coolant would become irrelevant. The whole factory would get shrunk in size and so is the activities. As the part is completed in one machine, the whole supply chain system existing within and outside the factory is expected undergo a sea change.

The technologies available in metal additive manufacturing are powder bed fusion, directed energy deposition, wire fed deposition and binder jet. Powder bed fusion system is leading the front with maximum applications under its scope. Directed energy deposition is useful for building material over exiting part and build large size parts. Wire fed system offers the advantage of depositing material in bulk to have larger build volume. Binder Jet offers unique advantage for making ceramic powders. Binder Jet does not call for a special inert environment which is part of all previous processes. All the above technologies have similar challenges in quality, throughput, material integrity and cost of manufacturing [2]. Significant R&D is happening on all these forefronts of challenges in additive manufacturing technology. In metal additive manufacturing fabrication, the part undergoes cyclic heating and cooling resulting in repeated phase transformation. This complex nature of the process has effect on fatigue, micro structural and mechanical properties. Hence qualification and certification has been a challenge for adapting AM for structurally critical components[3]. Higher layer thickness is a hindering factor in achieving surface quality. But for the wire based methods, other three processes use metal powders which costs high. Also, adding up the cost is the necessity of inert environment for certain materials to avoid oxidation during part building.

CMTI has pioneered introduction of AM technology in the country since 90's. Having expertise in machine building and as well in AM technology, CMTI is trying to address the challenges of AM in many ways.

2. CHALLENGES IN AM TECHNOLOGY

2.1 Throughput

To increase throughput, development is happening to use multiple lasers, array of diode lasers, multiple nozzles for material deposition. Presently, in metal additive manufacturing fibre laser is used to scan the metal powder spread over a platform. As the scanning takes place line by line, time required to build the part is quite high which is not enabling AM to move from smaller lot to bigger lot production. LLML came out with an AM technique [4] to melt entire layer of powder bed in single go using array of diode laser and programmable masks. LLML claims that diode lasers are 20 times cheaper than the currently used fibre lasers. X-Jet of Israel has launched its new path breaking product in AM recently. X-Jet uses nano particles in liquid suspension to build 3D metal parts. X-Jet's print head system uses cartridges filled with nano particles in liquid suspension to deposit fine layer of liquid droplets on system tray. Liquid droplets are injected by thousands of printing nozzles simultaneously [5]. X-Jet claims that it is 5 times faster than commercial laser based systems. Increasing the power of laser is one way of increasing the productivity; however the cost of the laser is a forbidding factor. If the productivity is increased by 10 times everybody would jump to additive manufacturing. So the challenge is to address how AM can achieve 10 times productivity from the present level.

2.2 Standards and Protocols

Standards are required for qualification from design stage, raw material stage, during processing, and after the part is built. Standard file format for use in AM equipment is needed. Standards are required to qualify the metal powder size, shape and uniformity.

2.3 Process Monitoring and Control

Challenge is to ensure quality while the part is built. Quality of each layer has to be ensured. Real time monitoring and control of each layer is required for quality part production from AM process [6]. Process monitoring & control has to be in closed loop with AM process. This will address part geometry requirement, distortion, micro structure requirement and residual stress in parts.

2.4 Accuracy and reproducibility

Improvement of dimensional accuracy is one of the major scientific challenges to enhance the qualities of the products produced by AM. Compared to conventional process, it is required to know where does AM parts stand in terms of achieving geometrical and dimensional accuracies. Weaver et al [7] had carried out experiments on to determine the tolerance for AM by concept laser metal additive machine through the NIST test artifact. Based on the experiments and tolerance derived, additive manufacturing is compared with established processes and showed that AM parts qualify for IT classes 11 to 16 according DIN EN ISO 286-1. AM is comparable to process casting, drop forging, drilling, and cutting with respect achievable accuracies. The parts made using the above traditional processes need to undergo further machining and finishing processes. Ultimate objective of AM is to avoid further processing once the part is built using AM process. The next challenge is to achieve tolerance class of IT 7 to IT 10 using AM process. Correspondingly the surface roughness value also needs to be achieved.

2.5 Surface Roughness

One of the key issues in Additive Manufacturing is the high surface roughness of up to 10micrometers, Ra. Layer thickness, metal powder size and processing parameters play an important role in deciding the surface roughness [8]. As of now, AM technologies are available to a layer thickness of 20 micrometers. It is necessary to reduce the metal powder size to reduce the layer thickness. When the particle size reduced, there are issues in uniformly spreading the powders on platform for laser sintering. Challenge is to get the surface roughness that is achievable on conventional processes without carrying out any post finishing process.

2.6 Mechanical Properties

Mechanical properties, tensile strength, yield strength, elongation, hardness, and fatigue limit are dependent upon the micro structural characteristic of the part. In additive manufacturing, powder quality has a significant impact on final properties of parts. AM industry does not have the confidence that the identical metal powders would result in parts of identical mechanical properties. Mechanical properties varies if recycled metal powders are used. Mechanical properties again varies in vertical andhorizontal build direction of the part.

2.7 Thermal Stresses and Deformation

In Additive Manufacturing (AM) residual stresses affects dimensional accuracy and causes premature fatigue failure, delamination and buckling of components.AM process involves cyclic heating and cooling of layers. When the melting and cooling process involves temperature gradients, thermal stresses develop. These stresses arise from the contraction or expansion associated with the deposition of a layer. The contraction results from strains when the layer is deposited at a high temperature and then allowed to cool to room temperature. With the control over layer thickness, pre heating and pattern strategy for scanning, formation of stresses can be reduced. But the challenge lies in deciding the layer thickness, pre heating temperature and the type of pattern for scanning.

2.8 Modelling and Simulation

Simulation of AM gives outputs like residual stress, distance and porosity and their influence on part geometry. Simulation aides in optimising the process parameters to get quality parts. Scan pattern, pitch and scan velocity play an important role in reducing the distortion of AM part. Energy output of laser or E-beam decide the material properties. Modelling and simulation of AM process with the beam having varying energy input across its source is challenging. This is much more challenging at overlapping zones and at boundaries where the energy source needs to change direction. Use of nano particles in AM modelling and simulation is another area where potential exists for addressing the challenges.

The other challenges that need to be addressed in AM are requirement of standards and qualification of process and parts, need for support structure and removal, porosity, need for inert atmosphere, limited material processing capabilities, post processing of metal powders, uniformity of metal powders, metal powder wastage, availability of software for design of AM parts, high cost of the machine, cost of the final product and safety.

2.9 Raw Material for Additive Manufacturing

Raw material for additive manufacturing is in powder form. Metal powders are produced by various methods. The most widely used process is gas atomisation process. Due to the nature of process, the raw materials produced by this process is expensive. This leads to high cost of input raw material for making metal parts. Challenge is to reduce the cost of metal powders for additive manufacturing.

3. R&D OPPORTUNITIES FOR ADDRESSING THE CHALLENGES IN AM

AM has opened plethora of R&D opportunities. It is required to use multi physics approach to understand the basics of AM. Thermal fluid dynamics calculations can then be used to predict melting behaviour, sub-surface morphology, and porosity. Improved through put by scanning entire surface of the layer. The need to improve the surface finish by reducing the powder sizes and layer thickness without compromising production rate. The need to increase dimensional accuracy and repeatability of parts potentially through in-situ metrology and combined model based approaches. It is essential to establish procedure for recycling and reusing the materials by AM process. AM gives opportunities for developing new products using functional gradient materials and epitaxial metallic structures. Limited material options necessitating the need for new materials. Modelling and simulation of the AM process is one of the major research area. Supporting design tools and methodologies which aid with the design for AM process to unlock the true potential of the technology has to be developed. Standards and protocols has to be developed for building AM parts.

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BN Manjunath, Scientist –B, Additive Mfg. (AMT) Dept. of Central Manufacturing Technology Institute (CMTI), Bengaluru. He holds Bachelor of Engg degree from National Institute of Engineering, Mysore. He has more than 05 years of professional experience in the field of additive manufacturing. His significant contributions includes development of technologies for refurbishment of automobile and aerospace components, development of new materials using AM technologies.

Vinod AR, Scientist - C Additive Mfg. (AMT) Dept. of Central Manufacturing Technology Institute (CMTI), Bengaluru. He is graduated in Mechanical Engineering from University of Kerala, Thiruvananthapuram in 2007. He has worked as Mechanical Engineer at Integrated Rural Technology Centre, Palakkad and as Junior Research Fellow at Naval Physical and Oceanographic Laboratory, Cochin. He has 9 years of research experience. He is presently working in the field of additive manufacturing using laser–based Powder Bed Fusion and Directed Energy Deposition Technologies. His areas of research interest are metal matrix composites, bimetallic parts, hardfacing and remanufacturing. He has published 9 technical papers in national and international conferences and journals.

S K Verma, Scientist 'F', Head Aerospace Laboratory (ASL) at CMTI, Bengaluru. He holds Bachelor of Engg degree from Jabalpur University and a MBA in Finance from Sikkim Manipal University. He has got 29 years of experience in the field of Design, Mfg, Hydraulics/Pneumatics & Mechatronics. His areas of research interests include Design, Simulation, Materials, FEA, PKM, Robotics & Automation. His Significant Contributions include Arc welding robot, Design & development of PKM, Aerostatic spindle for milling applications, Design of 350T Stud Tensioner, Servo hydraulic actuator for aerospace applications, Design of Hydraulic circuit for Various capacities of SPM's, Qualification testing of Servo hydraulic actuator, Sphere lapping attachment for CNC lathe. (Email: vermask.cmti@nic.in)

Dr N Balashanmugam, Joint Director, CMTI, Bengaluru. He obtained his BE (Hons) and ME (Prod) degrees from P. S. G College of Technology, Coimbatore. PhD degree from National Institute of Technology (NITK), Surathkal. He was a UNIDO fellow at Lehigh University, Bethlehem, Pennsylvania, USA. Since 1986, he has been working in CMTI and involved in development of more than fifty prototypes of machines and special purpose machines, made in CMTI. Dr N Balashanmugam has made vital contributions towards establishment of Nano Manufacturing Technology Centre, first of a kind mega project in India. He has twoinventions(patent pending) to his credit and published many papers in Journals and Conferences. (E-Mail: balashanmugam.cmti@nic.in)