भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

A Report on

TEQIP Workshop on Principles of Additive/Generative Manufacturing Technologies

Held on

1st to 5th December 2014
at IIT Hyderabad

Hosted by

Department of Mechanical & Aerospace Engineering,
Indian Institute of Technology Hyderabad

Sponsored by

National Project Implementation Unit
Under Ministry of HRD, GoI

Contents

Introduction

Additive Manufacturing (AM) processes (also known as 3D Printing, Rapid Prototyping and Manufacturing) create objects by material addition instead of removal. Paired with Computer-Aided Design (CAD) tools, AM techniques facilitate and/or afford the creation of new types of objects with unique geometrical and material properties, which cannot be created using conventional means. While AM is widely referred as the new industrial revolution, in reality there are still significant hurdles for successful commercialization of many of the technologies that adopt the principles of additive manufacturing. In addition, designing for AM is very different from that of design for conventional manufacturing processes. These hurdles are hindering the realization of full potential of AM in the industry, although, of late, many industries have started using/exploiting AM for a variety of applications (like apparel to aerospace). Keeping in view the ever changing manufacturing scenario, the academic institutions thus have to play a bigger role in expanding the research and training activities related to AM. Hence, KIT (Knowledge Incubation for TEQIP-II) at IIT Hyderabad planned to conduct this five-day workshop for TEQIP colleges on the principles of AGM processes. The workshop focused on the fundamental principles behind various AGM processes and also involved hands on training on use of 3D Printers.

While the 2-day workshop held on 7-8 July acted as a general introduction to AGM, the current 5-day workshop aimed to equip the participants with the fundamental principles along with the hand on training on use of 3D Printers. Hence, participants of the earlier workshop as well as new members will be equally benefited from the workshop.

Schedule

	Session-1	Session-2	Session3	Session4	Session5
Day-1	Registration & Welcome Remarks	Introduction to AGM: Classifications & Process Chain	Introduction to AGM: Classifications & Process Chain (cont)	Visit to the Manuf Lab in Workshop	
Day-2	Data Formats for AM ; interconversion of various formats	Applications: Aerospace	Data Validity Checks and Repair Procedures	Demo of Software: CAD & Deskartes	
Day-3	Slicing & Areafilling Algorithms	Sheet Lamination (LOM, UC)	Slicing & Areafilling Algorithms (cont..)	3D Printing Session Demo: Loading the parts, build time estimate, support removal and cleanup	
Day-4	Photopolymerization (SLA, Perfactory)	Material Extrusion (FDM)	Photopolymerization (SLA, Perfactory) (cont...)	Powder Bed Fusion (SLS)	Binder Jetting (Zcorp 3D Printing); Material Jetting (Objet)
Day-5	Direct Energy Deposition (LENS)	Applications: Bio-Medical	Introduction to Generative Manufacturing	Visit to Generative Lab in Kandi	

Day-1 of the Workshop

Welcome address *by Prof. Eswaran* (HoD, MAE, IITH)

On behalf of Department of Mechanical & Aerospace Engineering, IIT Hyderabad, Prof. Eswaran extended a warm welcome to all the participants. While highlighting the newly introduced course of Digital Fabrication for BTech first year students of all streams, he reminded the participants of the growing popular interest in 3D Printing. While emphasizing the need for Indian Academia to catch the moment, he hoped that the current workshop will be one step in that direction.

Introduction to AGM: Classifications & Process Chain (2-Sessions) *by Dr. Suryakumar* (Faculty, MEA,IITH)

Initiating the technical talks for the day, Dr. Suryakumar discussed the state-of-art, fundamental concepts and process chain for AM. This domain is identified with many names like Rapid Prototyping, Rapid Tooling, Rapid Manufacturing, Solid Freeform Fabrication (SFF), Layered Manufacturing, 3D Printing, Additive Manufacturing. Although it started as a design visualization tool, the applications of AM today include aerospace, automobiles, nuclear, fashion, edibles, medical implants, tissue engineering, printed electronics etc.

The following are the major steps in the process chain of AM:

1. Conceptualization and CAD
2. Conversion to STL
3. Transfer to AM Machine and STL File Manipulation
4. Machine Setup
5. Build

6. Removal and Cleanup
7. Post-process
8. Application

The following is the classification of various AM processes based on ASTM Committee F42 on Additive Manufacturing Technologies formed in 2009 and ISO/TC 261 committee on Additive Manufacturing created in 2011:

- Binder Jetting
- Direct Energy Deposition
- Material Extrusion
- Material Jetting
- Powder Bed Fusion
- Sheet Lamination
- Vat photo-polymerization

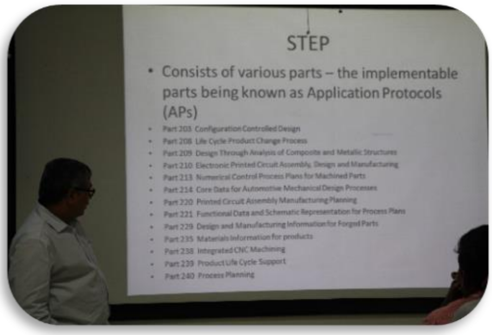
These various AM processes are discussed in greater detail in the subsequent part of the workshop.

Visit to the Manufacturing Lab in Workshop

The following are some of the machines/facilities displayed during the lab visit to the Manufacturing lab in IIT Hyderabad:

- Commercial scale FDM based 3D printer
- Low cost FDM based 3D printer
- Robotic welding station for weld-deposition
- Laser pointer based 3D Scanner

Data Formats for AM & Interconversion of Various Formats *by Prof. Venkata Reddy* (Faculty, MEA, IITH)



.STL format is a de-facto standard of layered/additive manufacturing. STL name originates from the process (stereo-lithography) for which this format is developed by 3D systems. The STL file format represents the surfaces of solid models as triangles. Generally, CAD packages provide option for breaking down models into STL format through a process called tessellation. The result of the tessellation is a file in either ASCII or binary form. Triangulated model deviates from original model and sometimes the intent of designer is also lost. Therefore, attempts have been made to use the CAD data (IGES and STEP) directly instead of going through tessellation process.

STL, IGES and STEP formats along with their advantages/limitations are discussed. In addition, demonstration/practice session sessions were held to gain hands-on experience.

Applications: Aerospace *by Dr. U Chandrasekhar* (Secretary & Director General, IE(I) & Director, ESCI)

Dr. U Chandrasekhar with his vast experience in AM and Aerospace Research discussed some of the applications of AM in Aerospace industry with the help of case studies. The fuel nozzle in the Leap X engines of GE is a good example for ability of AM to drastically change the manufacturing paradigms. This fuel nozzle made through the AM route combined 20 difference pieces into a single component, reduced the weight by 25% and five time durable in comparison to the existing design.

The growing number of companies setting up production scale AM facilities for metal symbolize the increasing acceptability of this process even in conventional domains and the transformation of AM from a secondary manufacturing option to the primary role. Aeronautical, Automotive, Biomedical / Dental, Defence, Electronics, Marine are some of the evolving domains of AM. Concepts like Mobile Parts Hospital (MPH), Innovation in producing 3D Printing Filaments from plastic waste, 3D Printing from Eco Friendly Materials were also discussed.

Data Validity Checks and Repair Procedures *by Prof. Venkata Reddy* (Faculty, MEA, IITH)

Due to the nature of STL file creation, sometimes repair becomes essential to rectify geometry related errors such as

- Gaps, cracks, holes, or punctures due to missing facets
- Overlapping facets.
- Degenerate facets in which all of the vertices (and thus all of the edges) are nearly collinear
- Non-manifold topology conditions.

In this module, the following aspects are emphasized

- Reasons for the above mentioned errors
- Procedures/Algorithms for identification of such errors
- Procedures/Algorithms for rectifying the identified errors

Demonstration/practice session was conducted using an in-house developed system.

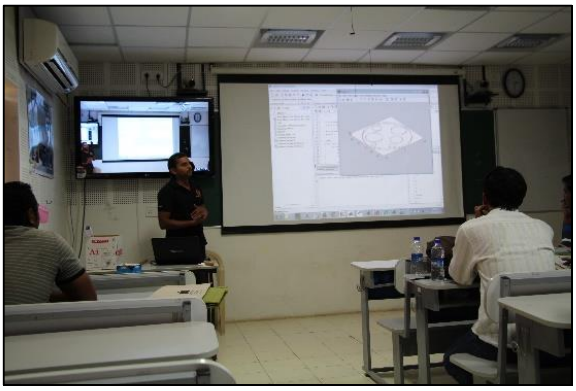
Demo of Software: CAD & Slicing

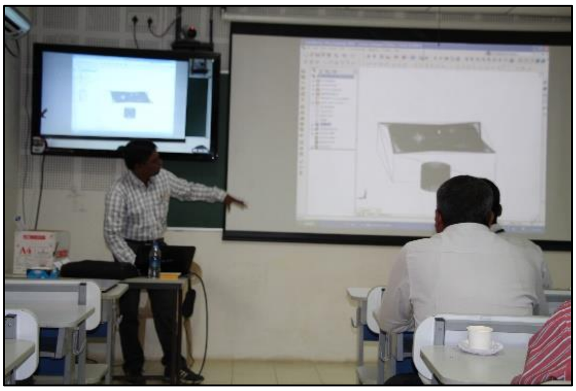
A demonstration of some commercial software in addition to the codes developed by the students of IITs was done in this session to create a better understanding amongst the participants about various project ideas and resources related to AM.

The following are some of the demonstrations made during the session:

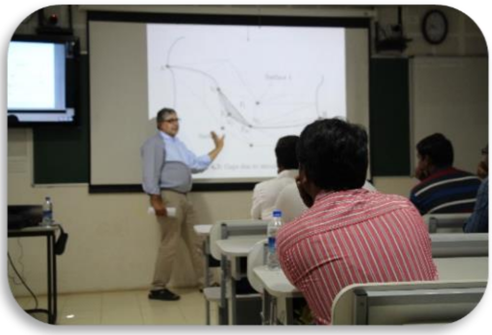
- Modelling of a simple part using CAD packages (demonstrated on SolidEdge platform)
- Exporting the CAD model into STL format and considerations of size vs accuracy
- Error correction in STL files
- A MATLAB code developed as part of course project for adaptive slicing of STEP files

- Area-filling patterns available on open-source softwares like Slice3r
- Conversion of CT scan data into CAD data using medical imaging software like Magics





Slicing & Areafilling Algorithms (2-Sessions) *by Prof. Venkata Reddy* (Faculty, MEA, IITH)



Additive Manufacturing (AM) or rapid prototyping is a process in which a part is produced using layer-by-layer addition of the material. In AM, slicing of the CAD model of a part to be produced is one of the important steps. Slicing of CAD model with a very small slice thickness leads to large build time. At the same time if large slice thickness is chosen, the surface finish is very bad due to stair-stepping. These two contradicting issues namely reduction in build time and better surface quality have been a major concern in laminated manufacturing. This contradiction has led to the development of number of slicing procedures. This module discussed various slicing approaches developed for triangulated/tessellated (STL) as well as actual CAD (IGES/STEP) models. The deviation of the CAD models with actual surface of produced prototype is quite large if the data preparation involves slicing of tessellated CAD models. Therefore, attempts have been made to adaptively slice a typical three-dimensional CAD model by using corresponding IGES/STEP file as input. A grid of points has been generated on each surface of a NURBS-based CAD model and slicing polygons are directly generated. The fineness of the grid is a measure of deviation of surface of produced prototype with actual CAD model.

Demonstration/Practice session was also arranged to emphasize the differences between slicing of .STL and IGES/STEP CAD models.

In any AM process, a three-dimensional polyhedral solid is built as a stack of two-dimensional slices. Each slice, which is basically a polygon, is built by filling its interior with a sequence of parallel line segments in a process called hatching. Clearly, while doing so, the apparatus needs to first decelerate and then accelerate at the end and start of each parallel segment, respectively, which adds to the overall slice deposition time. Different hatching/filling approaches present and their implications are discussed during this module.

Sheet Lamination Processes ***by Dr. Suryakumar*** (Faculty, MEA,IITH)

Laminated Object Manufacturing (LOM), was developed and commercialized by Helisys, USA is one of the most popular methods of RP is to make the required object by gluing the required laminates together. Each such slice can be cut from a sheet of paper and pasted one over the other. One can adopt one of the two approaches in this manufacture: (a) Cut-and-paste approach (b) Paste-and-cut approach. The paste-and-cut approach is suitable for non-metallic laminates of lower thicknesses. This is the reason why both popular LOM processes (Helisys and Kira) use this approach. On the other hand, when metallic sheets or thicker layers are used, the laminates will be sufficiently stiff for handling and hence paste-and-cut approach can be used. Furthermore, decubing is extremely difficult when the laminates are metals.

Only the boundary loops of the slice profiles need to be traced by the laser. Therefore, the time taken to build the prototype in LOM is proportional to its surface area. LOM has the potential to be a fast process. However, this advantage is eclipsed by the time spent in grid cutting and decubing.

Kira Corporation, Japan developed an AM system similar to LOM. This uses standard printing paper that is fed into the machine using a conventional laser printer. The printer uses an adhesive-based toner to print the outline of the cross-section as well as a cross-hatched bonding pattern on each piece of paper. A hot plate then laminates the paper to the previous layers. The cross-sectional outline is then cut with a carbide knife that is mounted on a swivel base.

Another recent significant process of this category is Ultrasonic Consolidation (UC) developed by Solidica, USA. It makes use of ultrasonic welding for joining the laminates. UC has been found suitable for joining Al and Cu strips as well as making Metal Matrix (MMX) objects. Of late, UC is finding applications in satellites to embed electronics (wiring, sensors, fibres and other functional devices) within a fully dense aluminium structure.

Part Deposition Orientation ***by Prof. Venkata Reddy*** (Faculty, MEA, IITH)

Part deposition orientation is very important factor of layered manufacturing as it effects build time, support structure, dimensional accuracy, surface finish and cost of the prototype. A number of layered manufacturing process specific parameters and constraints have to be considered while deciding the part deposition orientation. Determination of an optimal part deposition orientation is a difficult and time consuming task as one has to trade-off among various contradicting objectives like part surface finish and build time.

In this module, different algorithms available are discussed and their advantages/limitations are emphasized.

Hands-on Session on 3D Printing

A hands-on session on use of 3D printing machines was organized to train the participants on the same and also make them better understand the intricacies of the technology. The participants were divided into groups of three and each group was asked to conceptualize a part, design and model it in CAD and finally 3D Print it. Concepts of “Design for AM” in addition to time and cost estimation models formed the prelude to these same. Finally, the participants manufactured the designed parts in the 3D printers available in the Digital Fabrication lab of IITH. This included training on machine preparation, loading and firing of the STL file, post processing and support cleaning. This was followed by a comparative study of on open-source machines and commercial machines available in the market.

Photopolymerization Processes (2-Sessions) ***by Prof. Venkata Reddy*** (Faculty, MEA, IITH)

Stereo-lithography (SLA) or laser lithography is the first and most widely used RP/RT/RM process and many variants of the same process have come into existence over last two decades and based on photo-polymerization. Photo-polymerization processes can build three dimensional objects through selective polymerization of photosensitive polymers layer by layer. The energy necessary for polymerization is typically obtained by directing a UV laser source at the required location using a computer controlled lenses.

Prediction of cured profile geometry, dimensions and degree of polymerization in a profile was discussed. Various strategies to achieve uniform curing in a component were also emphasized.

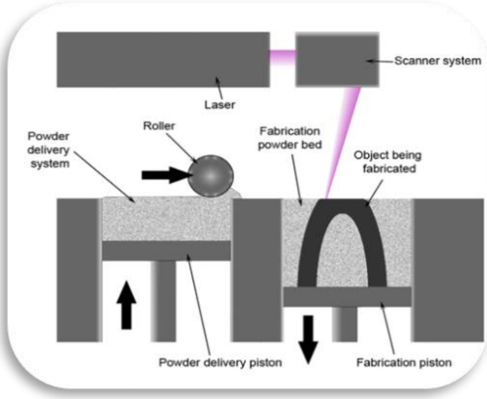
Material Extrusion Processes ***by Prof. Venkata Reddy*** (Faculty, MEA,IITH)

FDM selectively deposits a continuous filament of a thermoplastic polymer or wax through a resistively heated nozzle. It was developed and commercialized by Stratasys, USA. FDM can build parts out of Acrylonitrile Butadiene Styrene (ABS) plastic and Investment Casting Wax (ICW). Medical grade ABS thermoplastic and elastomers also are available. The following are some of the strengths and weaknesses of the process:

- Strengths
    - The machine is less expensive.
    - Variety of materials can be used and the material changeover, which involves only changing the head, is very fast and simple.
    - No post-curing is required.
    - There is little wastage of material.
    - The part building can be carried out unattended. The material has a large shelf life and remains unaffected if not removed from the packing provided.
- Weaknesses

- Surface finish and delicate features are inferior to other processes.
- The process is slow on bulky parts.
- The strength is low in the vertical direction.
- Accuracy & surface finish is less as compared to the other RP processes

Powder Bed Fusion Processes *by Dr. Suryakumar* (Faculty, MEA, IITH)



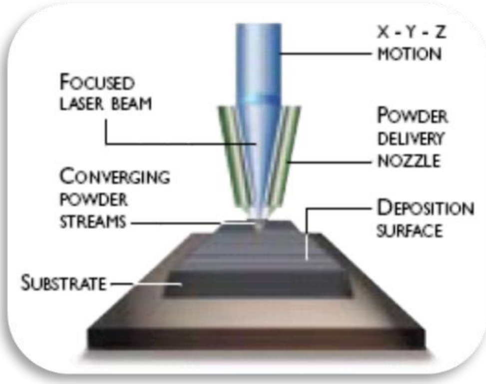
Selective Laser Sintering (SLS), the most prominent of the powder bed fusion processes, was originally developed at the University of Texas at Austin. In SLS a layer of powdered material is spread out and levelled over the top surface of the g rowing structure. A laser then selectively scans the layer to fuse those areas defined by the geometry of the cross-section; the laser energy also fuses layers together. The unfused material remains in place as the support structure. After each layer is deposited, an elevator platform lowers the part by the thickness of the layer, and the next layer of powder is deposited. When the shape is completely built up, the part is separated from the loose supporting powder.

Binder Jetting & Material Jetting Processes *by Prof. Venkata Reddy* (Faculty, MEA, IITH)

The first process that successfully demonstrated used Binder Jetting was the Three-dimensional Printing (3DP) process which was developed at MIT as a method to form "green" preforms for powdered metallurgy applications. In 3DP, the part is built up in a bin that is fitted with a piston to incrementally lower the part into the bin. Powder (such as alumina) is dispensed from a hopper above the bin, and a roller is used to spread and level the powder. An ink-jet printing head scans the powder surface and selectively injects a binder (such as colloidal silica) into the powder. The binder joins the powder together into those areas defined by the geometry of the cross-section. The unbound powder becomes the support material. When the shape is completely built up, the "green" structure is fired, and then the part is removed from the unbound powder. 3DP of metal powders, such as stainless steel bound with a polymeric binder, is also being possible; subsequent infiltration of the matrix is then required for densification.

A slight variant of the process is when the material itself is directly jetted instead of the binder. This has been successfully implemented by Objet systems. Its Polyjet matrix 3D printing uses simultaneous jetting of multiple types of modeling materials to create a single piece 3D model. A multiple jets are used, different multi-colour and multi-material prototypes are also possible using this technology.

Direct Energy Deposition Processes *by Dr. Suryakumar* (Faculty, MEA, IITH)



Laser Engineered Net-Shaping (LENS) originally developed at Sandia National Laboratory, USA, and further developed and marketed by OptoMec, USA, is the most popular commercial RM process capable of handling a variety of metallic powders including Titanium. Its deposition head uses 1 kW or 2 kW laser which is at the centre. It is surrounded by 2 or 4 nozzles. This head is mounted on a XYZ manipulator. When the head is moved over a substrate, it creates a moving weld pool into which the powders from the nozzles dive and get integrated. As the powder used is fine, fluidized feeding using Argon is em ployed. By moving the welding head along appropriate raster and contouring paths, the object is built in layers. It permits usage of different powders through different nozzles with the ability to control their flow rate independently. Thus, LENS is capable of building gradient objects. LENS has been successfully tested not only for fresh objects but also for repair of aerospace components.

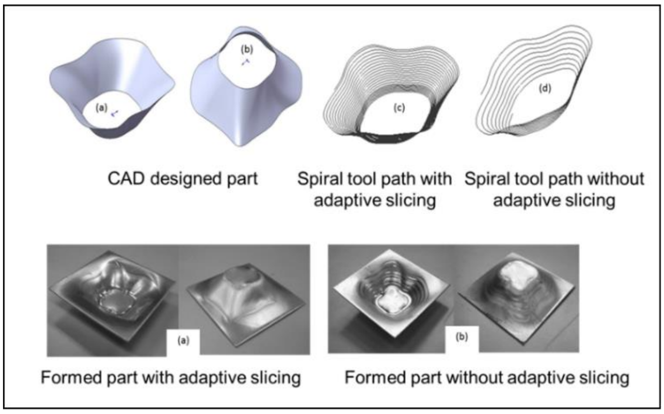
LENS is a pure additive process and hence produces only a near-net shape which requires finish-machining on a separate machine. Furthermore, building the near-net object is totally automatic only for the object built vertically. LENS does not use any support mechanism. Therefore, objects with undercuts and intricate shapes have to be built by suitably orienting the substrate.

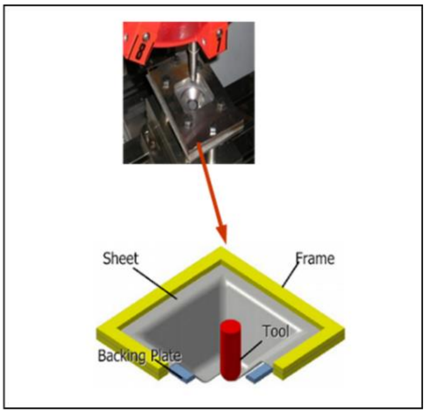
Applications: Bio-Medical *by Dr. Subha Narayan Rath* (Faculty, BM, IITH)

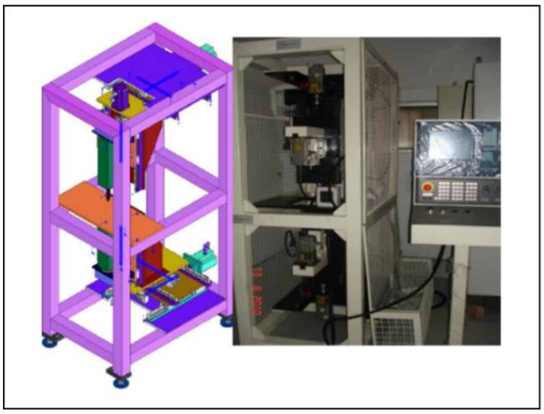
The following is the abstract of the talk by Dr Subha Narayan Rath on the subject of Bio-Medical applications of AM: “Additive manufacturing or 3D printing starts with a computer-assisted design (CAD) file where the lay-out of the printed object is planned. This file is modified into stereolithography (STL) file where the object is digitally sectioned into a series of 2D thin slices and later sent to a 3D printer to print the object layer by layer. It has a unique role to play in tissue engineering field which deals with using biomaterial scaffolds, cells, and suitable growth factors to develop biological substitutes to restore the function of any organ. The main used role of this technique is to manufacture a highly porous 3D scaffold from biomaterials. This technique can help us making different scaffold geometry, functionality, and shapes to be used as proper scaffolds for tissue engineering application. A set of sterile surgical instruments or a highly complicated geometry prostheses could be manufactured using this technique. Currently, active research is pursued by different groups to use cells and biomaterials by different print-heads to produce organs on demand. This might answer the organ shortage scenario in regenerative medicine application."

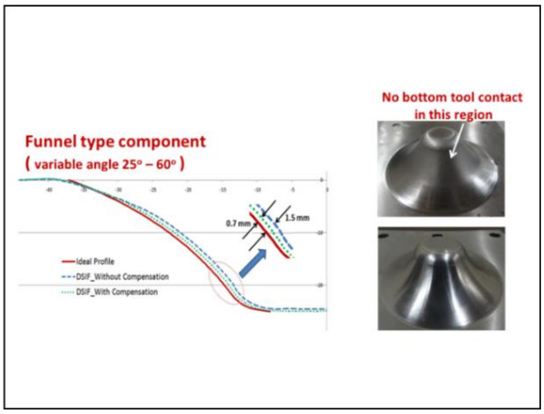
Introduction to Generative Manufacturing ***by Prof. Venkata Reddy*** (Faculty, MEA, IITH)

Incremental Sheet Metal Forming (ISMF) has demonstrated its great potential to form complex three-dimensional parts without using component specific tools against the conventional stamping operation. Forming components without component specific tooling in ISMF provides a competitive alternative for economically and effectively fabricating low-volume functional sheet metal products; hence, it offers a valid manufacturing process to match the need of mass customization, which is regarded as the future of manufacturing.









In ISMF process, sheet is clamped in a fixture/frame with an opening window on a programmable machine and a hemispherical/spherical ended tool is programmed to move in a pre-defined path giving shape to the clamped sheet by progressively deforming a small region in incremental steps. In ISMF, tool path plays an important role. Tool path generation is carried out using the contour information of different slices. Various aspects of AM that are useful for ISMF are emphasized during this presentation.

Visit to Generative Lab in Kandi

Participants visited ISMF facility in the Generative Lab in Kandi and had a demo of deep drawing and incremental forming machines. The Incremental Sheet Metal Forming machine installed there is capable of single point and multiple point ISMF.


Discussion on Teaching Resources & Closure

The final session of the workshop involved a discussion on the various teaching resources required for initiating a AM course and research in the respective institutions. A CD containing (a) all the slides of the workshop (b) relevant papers and (c) links to good process videos and websites was distributed to all the participants. The avenues provided by TEQIP for faculty training like a faculty being able to spend some time in the IIT as a tutor while attending other courses etc were also elaborated.

Group photo with the participants of the workshop

List of Participants

1	Mr. S. Sankar Ganesh Government of College of Engineering, Bargur
2	Mr. P. Natarajan Government of College of Engineering, Bargur
3	Mr. G. V. Subhash Sri Vishnu Engineering college for Women Bhimavaram
4	Mr. J. Teja Venkata Satish Sri Vishnu Engineering college for Women, Bhimavaram
5	Dr. Ravi Kumar Dwivedi Maulana Azad National Institute of Technology, Bhopal
6	Dr. Pradeep Kumar Soni Maulana Azad National Institute of Technology, Bhopal
7	Mr. R. Manu Madanapalle Institute of Technology & Science, Madanapalle
8	Mr. K. Vinod Kumar Sree Vidyanikethan Engineering College, Tirupathi
9	Smt. Ch. Prashanthi Gokaraju Rangaraju Institute of Engineering & Technology, Hyderabad
10	Mr. A. Raveendra Malla Reddy Engineering College Secunderabad
11	Mr. P. Chittibabu Anurag Engineering College Kodad
12	Mr. A. Damodara Reddy JNTUA College of Engineering Pulivendula
13	Mr. B. Vamsidhar Reddy JNTUA College of Engineering Pulivendula
14	Mr. Pola venkata Gopal Krishna Vasavi college of Engineering Hyderabad
15	Dr. P. Rama Lakshmi Chaitanya Bharathi Institute of Technology, Hyderabad
16	Ms. P. Anjani Devi Chaitanya Bharathi Institute of Technology, Hyderabad
17	Dr. R. Madhu Sudhan AU College of Engineering Visakhapatnam
18	Mr. P. Devi Prasad Aditya Institute of Technology & Management, Srikakulam
19	Mr. K. Srinivasa Rao Vasavi college of Engineering Hyderabad