ADDITIVE MANUFACTURING (AM)

Rev. A

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WHAT IS ADDITIVE MANUFACTURING (AM)

- ASTM F2972: (1) AM IS ‘PROCESS OF JOINING MATERIALS TO MAKE OBJECTS FROM 3-D CAD MODEL, USUALLY LAYER UPON LAYER, AS OPPOSED TO SUBTRACTIVE MANUFACTURING METHODOLOGIES. (2)

- SYNONYMS:
  3-D PRINTING, FREE FORM FABRICATION (FFF), DIRECT DIGITAL MANUFACTURING (DDM)

- AM DESCRIBES TECHNOLOGIES THAT CAN BE USED THROUGHOUT THE LIFE CYCLE OF A PRODUCT, FROM PREPRODUCTION (RAPID PROTOTYPING) TO FULL SCALE PRODUCTION (RAPID MANUFACTURING).

- AM STARTED WITH POLYMERS, THEN BRANCHED INTO METALS, CERAMICS & COMPOSITES

- AM IS A FAST, LOW-LABOR, PUSHBUTTON TECHNOLOGY

(1) STANDARD TERMINOLOGY FOR ADDITIVE MANUFACTURING TECHNOLOGIES, ASTM
(2) SUBTRACTIVE MANUFACTURING IS A RETRONYM COINED IN RECENT YEARS TO DISTINGUISH TRADITIONAL METHODS, SUCH AS MACHINING, FROM THE NEWER ADDITIVE MANUFACTURING TECHNIQUES
IMPORTANT ADDITIVE MANUFACTURING PROCESSES AT A GLANCE

SLA: STEREOLITHOGRAPHY
PBF: POWDER BED FUSION (1)
DED: DIRECTED ENERGY DEPOSITION (2)
FDM: FUSED DEPOSITION MODELING
UAM: ULTRASONIC ADDITIVE MANUFACTURING (3)
LOM: LAMINATED OBJECT MANUFACTURING

(1) PBF MOST RELEVANT TO NEW METAL PART PRODUCTION
(2) DED RELEVANT TO METAL PART REPAIR, REMANUFACTURE AND FEATURE ADDITION
(3) UAM IS SIMILAR TO LOM, BUT ONLY FOR METALS; LOM FOR PAPER, METALS & POLYMERS. IT IS NOT YET WIDELY USED IN THE AM FIELD. NOT FURTHER CONSIDERED HERE. FOR ADDITIONAL INFORMATION, SEE PAPER BY R. J. FRIEL AND R.A. HARRIS, PROCEDIA CIRP 6 (2013), PP. 35 – 40
(4) UV TECHNOLOGY IS NOT YET UTILIZED COMMERCIALLY IN THE AM FIELD. IT IS NOT FURTHER CONSIDERED HERE. FOR ADDITIONAL INFORMATION, SEE PAPER BY JERBY ETAL., 14 TH INTERNATIONAL CONFERENCE ON MICROWAVE AND HIGH FREQUENCY HEATING, AMPERE-2013, NOTTINGHAM, UK, SEPTEMBER 2013
LIQUID BASE AM
NOT RELEVANT TO FAA PROJECTS
LIQUID BASE AM- STEREOLITHOGRAPHY

- BUILD PLATFORM IMMERSED IN LIQUID RESIN, COVERED BY THIN LAYER (THICKNESS D)
- ULTRAVIOLET (UV) LASER CURES FIRST THIN LAYER PER CAD
  - LAYER BONDS (ADHERES) TO BUILD PLATFORM-MECHANICAL BOND
- PLATFORM DROPS DISTANCE D
  - THIN LAYER (THICKNESS D) IS NOW ON TOP OF FIRST LAYER
- UV LASER CURES SECOND LAYER PER CAD
  - LAYER TO LAYER ADHESION-MECHANICAL
- AND SO ON UNTIL PART IS COMPLETE
- PLATFORM IS RAISED
  - PART SEPARATED FROM BUILD PLATFORM AND CLEANED
STEREOLITHOGRAPHY, CONTINUED

- FIRST AM PROCESS (1986)
- CHARLES HULL INVENTED AND PATENTED PROCESS (1986)
  - COINED THE TERM STEREOLITHOGRAPHY
  - FOUNDED 3D SYSTEMS, INC.
    - TO COMMERCIALIZE PROCESS
- AKA VAT POLYMERIZATION, DIGITAL LIGHT PROCESSING
- ONLY FOR PHOTO-CURABLE RESINS (POLYMERS)
- ORIGINALLY USED FOR RAPID PROTOTYPING, THEN FOR PARTS
SOLID BASE AM
POWDER BED TECHNIQUES
POWDER BED TECHNIQUES

- INKJET. AKA BINDER JETTING, 3-D PRINTING
  - NOT RELEVANT TO FAA PROJECTS

- POWDER BED FUSION (PBF)
  - MOST RELEVANT TO NEW PART PRODUCTION IN FAA PROJECTS
POWDER BED TECHNIQUES
INKJET 3D PRINTING

- A LAYER OF POWDER IS SPREAD ON BUILD PLATFORM
- INKJET HEAD MOVES ACROSS POWDER BED
  - SELECTIVELY DEPOSITING A LIQUID BINDER (ADHESIVE) PER CAD
- PLATFORM DROPS BY ONE LAYER THICKNESS
  - ANOTHER POWDER LAYER IS SPREAD
- PROCESS REPEATS UNTIL PART IS COMPLETED
- ALLOW TIME FOR ADHESIVE TO SET BEFORE REMOVING PART
- PART NEEDS TO BE CURED OR HARDENED
  - OFTEN INFILTRATED
- FOR POLYMERS, CERAMICS, COMPOSITES METALS (STRUCTURAL?)
INKJET 3D PRINTING, CONTINUED

- DEVELOPED AT MIT
  - LICENSED TO Z CORP (1)
    - CODE NAMED PROCESS 3-D PRINTING
      - 3-D PRINTING IS ACRONYM FOR AM
  - LATER LICENSED TO OTHER COMPANIES
  - AKA BINDER JETTING

- SIMILAR PROCESS
  - POLYJET (STRATASYS-US)
    - PHOTOPOLYMER, UV INSTANT CURE

(1) NOW COLOR JET PRINTING SYSTEMS
POWDER BED TECHNIQUES, CONTINUED
POWDER BED FUSION (PBF)

- Layer of powder is spread on build platform / substrate
- Laser / electron beam moves across a bed of powder selectively fusing areas per CAD
- Platform drops by one layer thickness
- Another powder layer is spread on build platform / substrate
- Process repeats until part is constructed
  - Polymers, ceramics, composites, metals
- Part removed, separated from build platform / substrate, (1) cleaned from excess powder
- Part may need additional consolidation (e.g., HIP) or infiltration

(1) First layer bonds (adheres) to platform / substrate
POWDER BED FUSION (PBF), CONTINUED.

PBF TECHNOLOGIES

- Several technologies fall under the PBF, as confusingly branded by different manufacturers/users (patent and license concerns)
  - SLS (Selective Laser Sintering) (1) - Developed by Univ. of Texas, marketed by 3D Systems Group: (2)
  - DMLS (Direct Metal Laser Sintering) (1) - EOS (3) GmbH
  - SLM (Selective Laser Melting) - Used by SLM Solutions GmbH, Phenix Systems Group, (2) Renishaw, Inc., Realizer, Matsuura & others
    - SLM referred to as:
      - Direct Metal Laser Melting (DMLM) by GE
      - Laser Cusing (4) by Concept Laser GmbH
  - EBM (Electron Beam Melting) - Arcam (5)

(1) Some authors indicate that DMLS and SLS are similar. SLS is the general term used for glass, ceramics, glass and metal. DMLS is strictly for metals
(2) 3D Systems Group acquired the Phenix Systems Group
(3) Electro Optical Systems
(4) Cusing: Letter C from Concept Laser + Last five letters from Fusing (Complete Melting)
(5) Arcam AB, a Swedish company, manufactures the only powder bed electron beam system, the Arcam A2
POWDER BED FUSION (PBF), CONTINUED

- PBF MOST RELEVANT TO AM METAL & ALLOY NEW PART PRODUCTION IN FAA PROJECTS
  - POWDER BED EQUIPMENT MANUFACTURED BY COMPANIES OUTSIDE THE US

- COMPARED TO LPBF, EB PBF
  - LOWER RESIDUAL STRESS
    - RUNS HOTTER
  - FASTER BUILD RATES
  - ROUGHER FINISH
    - DUE TO COARSER POWDERS, THICKER LAYERS & LARGER MELT POOLS
    - NEEDS POST PROCESS MACHINING

- FUSION MEANS CONSOLIDATION OF THE POWDER

- CONSOLIDATION BY
  - MELTING OR SINTERING (SEE NEXT SLIDE)
  - DIFFERENT PROCESSES; BUT BOTH YIELD METALLURGICAL BONDS
  - WHETHER MELTING OR SINTERING DEPENDS ON
    - LASER / EB POWER
    - LASER TYPE
    - LASER MODE (CONTINUOUS, PULSED, ETC.)
    - SCAN SPEED

- UNFORTUNATELY, MELTING AND SINTERING USED INTERCHANGEABLY IN AM LITERATURE; E.G., SLS / SLM & DMLS / DMLM
  - ADDS TO THE CONFUSION
POWDER BED FUSION (PBF), CONTINUED
MELTING VS. SINTERING

- **MELTING**
  - COMPLETE MELTING
  - AS IN SLM AND DMLM
  - USED FOR PURE METALS & METAL ALLOYS

- **SINTERING** (1)
  - SOLID STATE SINTERING (SSS)
    - NO MELTING
    - CONSOLIDATION BY GRAIN BOUNDARY MIGRATION
    - SLOW
      - INCOMPATIBLE WITH DESIRED HIGH PRODUCTION RATES
    - NEEDS ADDITIONAL CONSOLIDATION
      - E.G., HIP AND INFILTRATION
    - USED FOR CERAMICS
    - NOT SUITABLE FOR PURE METALS
      - PURE METALS TRANSITION FROM SOLID STATE TO LIQUID STATE IN NARROW TEMPERATURE RANGE
  - LIQUID PHASE SINTERING (LPS)
    - PARTIAL MELTING
    - DISCUSSED NEXT SLIDE

(1) THE SINTERING PROCESSES DISCUSSED HERE ARE NOT ORDINARILY USED IN PRODUCTION OF THE METALLIC ENGINE AND AIRFRAME COMPONENTS USED IN AIRCRAFT
MELTING VS. SINTERING, CONTINUED
LIQUID PHASE SINTERING (LPS)

- LIQUID PHASE SINTERING (PARTIAL MELTING)
  - WITH BINDER
    - LOW MELTING BINDER + HIGH MELTING STRUCTURAL MATERIAL
    - BINDER MELTS AND BONDS STRUCTURAL MATERIAL PARTICLES
    - BINDER PERMANENT OR SACRIFICIAL
    - THREE TYPES OF STARTING MATERIALS
      - SEPARATE POWDER BINDER AND STRUCTURAL MATERIAL PARTICLES
      - COMPOSITE POWDER
        - ONE TYPE OF POWDER PARTICLES
          - CONTAINING BINDER AND STRUCTURAL MATERIAL
      - COATED PARTICLES
        - BINDER APPLIED AS COATING TO STRUCTURAL MATERIAL
    - NEED FURTHER CONSOLIDATION E.G., HIP AND INFILTRATION
POWDER BED FUSION (PBF), CONTINUED

ADVANTAGES & LIMITATIONS

- WITHOUT BINDER
  - JUST THE STRUCTURAL MATERIAL
  - ONLY A SHELL AT BOUNDARY OF EACH PARTICLE IS MELTED
    - CORE REMAINS SOLID
  - TWO TYPES OF MATERIALS
    - SINGLE POWDER
    - A MIXTURE OF DIFFERENT POWDERS

- ADVANTAGES
  - CAN BUILD COMPLEX PARTS, HOLLOW PARTS, PARTS WITH COOLING PASSES (E.G., BLADES)
  - GOOD SURFACE FINISH, HIGH PRECISION

- LIMITATIONS
  - LIMITED / NON-EXISTENT CAPABILITY FOR REPAIR & REMANUFACTURING
    - DUE TO HORIZONTAL LAYER CONSTRUCTION
  - LIMITED BUILD ENVELOPES & LOW DEPOSITION RATES
  - FEATURE ADDITION NOT POSSIBLE
  - SINGLE MATERIAL PER BUILD
SOLID BASE AM
DIRECTED ENERGY DEPOSITION (DED)
RELEVANT TO FAA REPAIR, REMANUFACTURE & FEATURE ADDITION PROJECTS
DED PROCESSES

- **POWDER FEED PROCESSES**
  - AKA POWDER DEPOSITION

- **WIRE FEED PROCESSES**
  - FUSION WELDING PROCESSES THAT ADD FILLER CAN BE USED IN AM
    - E.G., EWI HOT WIRE GTAW & RR SMD (SHAPED METAL DEPOSITION) - ALSO GTAW

**DED CAN BE USED TO**

- BUILD NEW PARTS
- REPAIR, REMANUFACTURE EXISTING PARTS
- ADD FEATURES TO EXISTING PARTS

(1) THERMAL & COLD SPRAY METHODS CAN ALSO BE USED IN A SIMILAR CAPACITY
DIRECTED ENERGY DEPOSITION (DED), CONTIN’D

- POWDER BED IN PBF REPLACED BY
  - CONCENTRIC POWDER DELIVERY NOZZLES
  - SIDE-FED WIRES

- POWDER FEED-LASER OR ELECTRON BEAM LASER SHOWN HERE

- WIRE OR POWDER FEED-ELECTRON BEAM
  - WIRE FEED SHOWN HERE

- WIRE FEED-PLASMA ARC
DIRECTED ENERGY DEPOSITION (DED), CONTINUED

- NEW PART CONSTRUCTION
  - PART IS BUILT LAYER BY LAYER, PER CAD, ON A BUILD PLATFORM / SUBSTRATE, AS IN PREVIOUS PROCESSES

- REPAIR, REMANUFACTURE AND FEATURE ADDITION
  - EXISTING PART PLACED ON BUILD PLATFORM / SUBSTRATE
  - PROCESSED LAYER BY LAYER, PER CAD, AS BEFORE

- LAYER TO LAYER, LAYER TO PART & LAYER TO PLATFORM / SUBSTRATE ADHESION
  - THROUGH MELTING (METALLURGICAL BOND)

- IN LASER POWDER FEED SYSTEMS
  - DEPOSITION HEAD REMAINS STATIONARY, WHILE WORKPIECE MOVES
    - OR
  - DEPOSITION HEAD MOVES, WHILE WORKPIECE REMAINS STATIONARY
SEVERAL TECHNOLOGIES FALL UNDER THE DED CATEGORY, AS BRANDED BY DIFFERENT MANUFACTURERS / USERS (PATENT AND LICENSE CONCERNS)

POWDER FEED-LASER, AKA LASER POWDER FORMING (LPF)

- **DMD (DIRECT METAL DEPOSITION)**
  - DEVELOPED AT THE UNIV. OF MICHIGAN
  - MARKETED BY THE POM GROUP, (1) INC.

- **LENS (LASER ENGINEERED NET SHAPING)**
  - DEVELOPED AT SANDIA (US)
  - MARKETED BY OPTEMIC, INC. (US)

- **LC (LASER CONSOLIDATION)-SIMILAR TO LENS**
  - DEVELOPED BY GE GLOBAL & NATIONAL RESEARCH COUNCIL-CANADA
  - LICENSED TO ACCUFUSION INC.-CANADA

- **CLAD (DIRECT ADDITIVE MANUFACTURING BY LASER)**
  - BeAM, OFTEN REFERRED TOO AS BEAM (FRANCE)

- **LASER CLADDING-POWDER** (2)

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(1) PRECISION OPTICAL MANUFACTURING DM3D TECHNOLOGY (US) ACQUIRED THE POM GROUP, INC.(US) IN 2013

(2) PROCESS UTILIZES A LASER TO METALLURGICALLY BOND A COATING TO A PART (SHALLOW MELT POOL). SIMILAR TO THERMAL SPRAY
DIRECTED ENERGY DEPOSITION (DED), CONTINUED
DED TECHNOLOGIES

- POWDER FEED-ELECTRON BEAM
  - EBFFF (ELECTRON BEAM FREEFORM FABRICATION)
    - SCIAKY (US)

- WIRE FEED-LASER
  - LASER CLADDING-WIRE (1)

- WIRE FEED-PLASMA ARC
  - PAAM (PLASMA ARC ADDITIVE MANUFACTURING)
    - DEVELOPED BY NORSK TITANIUM (NORWAY)
  - PTAS FFF (PLASMA TRANSFERRED ARC SELECTED FFF (2))
    - MER (3) CORPORATION (US)
  - IFF (ION FUSION FORMATION)
    - HONEYWELL (US)

- WIRE FEED-ELECTRON BEAM
  - EBF³ (ELECTRON BEAM FREEFORM FABRICATION)
    - DEVELOPED BY LOCKHEED MARTIN
    - STUDIED & IMPROVED BY NASA
  - EBFFF (ELECTRON BEAM FREEFORM FABRICATION) (4)
    - SCIAKY (US)

(1) PROCESS UTILIZES A LASER TO METALLURGICALLY BOND A COATING TO A PART (SHALLOW MELT POOL); SIMILAR TO THERMAL SPRAY. (2) FREEFORM FABRICATION. (3) MATERIAL AND ELECTROCHEMICAL RESEARCH. (4) FORMERLY EBDM (ELECTRON BEAM DIRECT MANUFACTURING)
DED TECHNOLOGIES, CONTINUED
DED ADVANTAGES & LIMITATIONS

DED ADVANTAGES

- Faster deposition rates than PBF (Wire feed > Powder feed)
- Larger build envelopes than PBF (Wire feed > Powder feed)
- More suited than PBF
  - For repair, remanufacture & feature addition
- Able to deposit multiple materials in a single build
- Some DED systems have nozzles with channels that supply shielding gas
  - No need for enclosed chambers

DED LIMITATIONS

- Coarse surface finish
- Limited for construction of new complex & hollow parts and parts with cooling passes (e.g., blades)
- Parts produced by wire feed systems
  - More extensive machining than those produced by PBF (1)
    - Wire feed more so than powder feed

(1) In general, processes that provide high deposition rates favor production of parts that require post-process machining. Processes that provide lower build rates offer superior quality.
METALLURGY-METAL MELT PROCESSES

- MELT PROCESSES INVOLVE LAYER BY LAYER DEPOSITION
  - EACH LAYER IS CAST HOT UPON A PREVIOUS LAYER
  - PREVIOUS LAYER IS COOLING DOWN
- COMPLEX, TIME DEPENDENT TEMPERATURE PROFILES.
  - TEMPERATURE PROFILES DEPEND UPON
    - AM EQUIPMENT
    - TIME BETWEEN PASSES
    - PART SIZE
    - DEPOSITION RATE
    - HEAT INPUT
    - CHARACTERISTICS OF INPUT MATERIALS
    - MANY OTHER FACTORS
  - ALLOY MAY EXPERIENCE REPEATED PHASE TRANSFORMATIONS
- MELT PROCESSES ALSO INVOLVE RAPID DIRECTIONAL SOLIDIFICATION
  - FREQUENTLY LEADING TO COLUMNAR GRAIN STRUCTURES.
COMBINED EFFECTS OF RAPID DIRECTIONAL SOLIDIFICATION & REPEATED PHASE TRANSFORMATIONS
- PROFOUND EFFECT ON MICROSTRUCTURE
  - HENCE, PART PROPERTIES

THICK LAYER DEPTHS ADVERSELY AFFECT BONDING (ADHESION)
- DEPTH OF MELT DOES NOT REACH BOTTOM OF LAYER

THIN LAYER DEPTHS SLOWS DOWN PROCESS

SCAN STRATEGY HAS PRONOUNCED EFFECTS ON PROPERTIES
- E.G., ON DENSITY (Ti-6 Al-4V)

HATCH DISTANCE (1) ALSO HAS PRONOUNCED EFFECT ON RESIDUAL STRESSES AND OTHER PROPERTIES

(1) DISTANCE BETWEEN ADJACENT SCANS
TO OBTAIN MORE ISOTROPIC PROPERTIES, IT MAY BE NECESSARY TO

- ROTATE SCAN DIRECTIONS WITH RESPECT TO EACH OTHER AND

- USE DIFFERENT SCAN PARAMETERS (SCAN SPEED, LASER POWER, HATCHING DISTANCE)

  - FOR SKINS, CORE & CONTOUR
LASER SURFACE REMELTING (LSR) CAN BE USED FOR

- **DENSIFICATION**
  - AFTER SCANNING A LAYER AND MELTING THE POWDER
    - SAME LAYER IS SCANNED AGAIN
  - BEFORE PUTTING A NEW LAYER

- **IMPROVING SURFACE QUALITY / FINISH OF CURVED OR INCLINED SURFACES**
  - REMELTING IS APPLIED ONLY TO Contour
    - TO ELIMINATE / MINIMIZE STAIR EFFECT (1)

(1) THE STAIR EFFECT IS A FEATURE IN ALL LAYERED MANUFACTURING TECHNIQUES FOR THE PRODUCTION OF CURVED OR INCLINED SURFACES
AM CAN BE USED TO
  - FABRICATE NEW COMPONENTS
  - ADDING FEATURES TO COMPONENTS
  - REPAIR EXISTING COMPONENTS

DIFFERENT THERMAL CONDITIONS IN EACH CASE

POST-DEPOSITION HEAT TREATMENT
  - MAY NOT BE POSSIBLE IN ALL CASES

DIFFERENT MECHANICAL PROPERTIES ANTICIPATED
SOLID BASE AM
WIRE / FILAMENT FEED TECHNIQUES-EXTRUSION
NOT RELEVANT TO FAA PROJECTS
WIRE / FILAMENT FEED-EXTRUSION
FUSED DEPOSITION MODELING (FDM)

- DEVELOPED BY STRATASYS INC. (US) IN 1989
  - USED FOR THERMOPLASTICS, EUTECTIC ALLOYS, WAX
  - AKA EXTRUSION AM, SEMI-SOLID FREEFORM FABRICATION

- WIRE FED INTO AN EXTRUSION HEAD
  - HEATED JUST BELOW MELTING POINT / RANGE
  - EXTRUDED THROUGH A NOZZLE
  - DEPOSITED LAYER BY LAYER ON PLATFORM PER CAD

- FIRST LAYER TO PLATFORM AND LAYER TO LAYER ADHESION
  - MECHANICAL-
  - SOME SOLID STATE DIFFUSION IN THE CASE OF METALS

- NEED SUPPORTS
  - EXTRUDED MATERIAL NOT STRONG ENOUGH

- SIMILAR PROCESS
  - FUSED FILAMENT FABRICATION (FFF)
SOLID BASE AM
SHEET STARTING MATERIALS
NOT RELEVANT TO FAA PROJECTS
SOLID BASE AM-SHEET
LAMINATED OBJECT MANUFACTURING (LOM)

- DEVELOPED BY HELISES, INC. (US) IN 1988
- UTILIZES LAYERS OF PAPER, METAL FOIL, PLASTIC FILM WITH ADHESIVE BACKING
- EACH LAYER HEATED BY A ROLLER
  - TO ACTIVATE ADHESIVE
    - BOND FIRST LAYER TO BUILD PLATFORM / SUBSTRATE
    - BOND TO LAYER BELOW
  - ADHESION-MECHANICAL
- PER CAD, AT EACH LAYER LASER CUTS
  - OUTLINE OF THE PART AT THAT LAYER
  - A BORDER AROUND THE BUILD AREA PER CAD
LAMINATED OBJECT MANUFACTURING (LOM), CONTINUED

- LASER CROSS HATCHES NON-PART AREAS PER CAD
  - CROSS HATCHES
    - FACILITATE REMOVAL OF WASTE MATERIAL
- AFTER A LAYER IS PROCESSED, BUILD PLATFORM DROPS
  - BY ONE LAYER THICKNESS
- ANOTHER LAYER IS LAID AND
- PROCESS IS REPEATED UNTIL THE BUILD IS COMPLETE
- THE BUILD, IN THE FORM OF A BLOCK BONDED TO
  PLATFORM IS REMOVED FROM MACHINE
  - BLOCK IS SEPARATED FROM PLATFORM & DE-CUBED TO REVEAL
    PART
    - SOMETIMES CHISEL NEEDED TO PRY CUBES AWAY FROM PART
- PART SANDED AND FINISHED
- LOW RESIDUAL STRESSES
ADDITIVE MANUFACTURING
OBSERVATIONS, USER CONCERNS &
PERSONAL VIEWS
OVERALL LEVEL OF AM ACTIVITY AND INFRASTRUCTURE IN EU GREATER THAN THAT IN US

ENGINE MANUFACTURERS WERE FIRST TO RECOGNIZE AM AS ATTRACTIVE MEANS TO BRING THEIR COMPLEX PARTS TO PRODUCTION

- AIRFRAME MANUFACTURERS ARE CATCHING ON
  - BALD (BLEED AIR LEAK DETECT) BRACKETS, Ti-6-4, EB PBF PLUS HIP
    - LOCKHEED MARTIN AND OAK RIDGE NATIONAL LABORATORY
    - F-35 (JOINT STRIKE FIGHTER)
  - IN 2015, AIRBUS ANNOUNCED:
    - THE NEW AIRBUS 350 XWB CONTAINS OVER 1000 AM PARTS

ASTM STANDARDS COMMITTEE F 42 FOR AM ESTABLISHED 2009

- DEFINE AM TERMINOLOGY, M & P, TEST METHODS & DESIGN
  - ASTM F2972: STANDARD TERMINOLOGY FOR ADDITIVE MANUFACTURING TECHNOLOGIES
  - ASTM F2924: STANDARD SPECIFICATION FOR ADDITIVE MANUFACTURING TITANIUM-6 AI-4 V WITH PBF
  - ASTM F3001: STANDARD SPECIFICATION FOR ADDITIVE MANUFACTURING TITANIUM-6 AI-4 V ELI (EXTRA LOW INTERSTITIAL) WITH PBF

- COMMITTEE F 42 WORKING WITH ISO TC 261
  - TO DEVELOP UNIFIED STANDARDS TO BE USED GLOBALLY
EWI ORGANIZED THE ADDITIVE MANUFACTURING CONSORTIUM (AMC) IN 2010:

SAE AMS ADDITIVE MANUFACTURING COMMITTEE (AMS-AM) LAUNCHED IN 2015
- AMS 4999: TITANIUM ALLOY LASER DEPOSITED PRODUCTS ~ 6 Al-4V-ANNEALED
  - THIS FOR DED PRODUCTS

AMERICA MAKES, FORMERLY NAMII (NATIONAL ADDITIVE MANUFACTURING INNOVATION INSTITUTE) LAUNCHED IN 2013
- FUNDED BY DOC, DOD, DOE, NSF, AND NASA ALONG WITH MULTIPLE INDUSTRIAL, ACADEMIC, AND NONPROFIT PARTNERS

NIST PROPOSED AN ARTIFACT (COMPLEX TEST PART)
- TO ASSESS AM CAPABILITIES

THERE IS AN ADDITIVE MANUFACTURING JOURNAL
- GOOGLE ADDITIVE MANUFACTURING JOURNAL-ELSEVIER
  - www.elsevier.com

THERE IS ALSO THE AMUG (ADDITIVE MANUFACTURING USERS GROUP)
- AN INDEPENDENT INDUSTRY-WIDE USERS GROUP
EFFORTS ARE UNDERWAY TO TAKE AM OUT OF THE CONFINES OF EXISTING TECHNOLOGIES

- BIG AREA ADDITIVE MANUFACTURING (BAAM) IS A DEVELOPMENT OF LOCKHEED MARTIN AND OAK RIDGE NATIONAL LABORATORY
  - SYSTEM CAPABLE OF MANUFACTURING COMPONENTS THAT ARE MULTIPLE YARDS IN ALL DIMENSIONS.
- IN THE NETHERLANDS, AN ARTIST IS USING AM TO MAKE FREEFORM POLYMER DESIGNS THAT ARE SEVERAL FEET LONG
- ALSO IN THE NETHERLANDS, THERE IS A PLAN TO USE AM TO BUILD A BRIDGE IN MID-AIR

AM CAN EMBED SENSORS IN MATERIALS AS THEY ARE BEING MANUFACTURED
- NOT POSSIBLE BEFORE

AM CAN BE USED TO PRODUCE PARTS DIRECTLY FROM A CAD FILE GENERATED BY REVERSE ENGINEERING, USING CT (COMPUTED TOMOGRAPHY) SCANS, CMM (COORDINATE MEASUREMENT MACHINE) DATA AND / OR LASER SCANNING
- EXPECT A FLURRY OF PMA ACTIVITY
  - GOD HELP THE FAA
SOME USER CONCERNS IN AM APPLICATION

- LACK OF CONSENSUS METHODS AND TEST DATA FOR QUALIFICATION AND CERTIFICATION
- LACK OF AM STANDARDS
  - BEING RECTIFIED BY ASTM, SAE, ISO TC 261 & OTHERS
- LACK OF PROCESS REPEATABILITY
- CAN PROPERTIES BE RELIABLY PREDICTED BY MODELING?
  - TESTING MAY BE DIFFICULT.
- LACK OF DATA SOURCES FOR MATERIAL & PROCESS SELECTION
- LACK OF EXTENSIVE STATISTICAL DATABASE (MMPDS STUFF)
  - RECENT ASTM F 42 / MMPDS INTERACTION NOT POSITIVE
- VARIATIONS IN INPUT MATERIALS (E.G., POWDER / WIRE SIZES, CHEMISTRY)
- EQUIPMENT & PROCESS VARIATIONS
- ANISOTROPY DUE TO
  - LAYERING
  - STITCHING
  - CORNERS, INTERSECTIONS
  - COLUMNAR GRAINS
PERSONAL VIEWS

- FAA SHOULD REMAIN INVOLVED IN THE AM EFFORTS INITIATED GLOBALLY BY VARIOUS ENTITIES
  - TO FAMILIARIZE OURSELVES WITH
    - APPLICATION METHODS
    - PROCESS PARAMETERS
    - INSPECTION REQUIREMENTS
    - MATERIALS AND PROCESSES SPECIFICATIONS
    - QUALIFICATION & LOT ACCEPTANCE PHILOSOPHIES
  - AND BE IN A BETTER POSITION TO ASSESS OEM AND AFTERMARKET AM SUBMITTALS

- MY UNDERSTANDING IS THAT FAA SELDOM APPROVES MATERIALS & PROCESSES AS STANDALONE ENTITIES
  - MATERIALS & PROCESSES APPROVALS ARE IMPLIED WHEN A PARTICULAR DESIGN HAS BEEN CERTIFICATED
    - REGARDLESS OF WHETHER THIS DESIGN IS A COMPONENT, AN ENGINE OR AN AIRCRAFT

- THEREFORE, WHY IS FAA ATTEMPTING TO REGULATE AM AS A STANDALONE ENTITY?

(1) A PART PRODUCED BY AM IS BOTH A MATERIAL AND A PROCESS
PERSONAL VIEWS, CONTINUED

- AM IS BEING USED
  - ON TRANSPORT CATEGORY AIRCRAFT (PART 25)
    - SUBJECT TO REQUIREMENTS OF
      - § 25.303 (FACTOR OF SAFETY),
      - § 25.613 (STATISTICAL DESIGN VALUES)
      - POSSIBLY § 25.619 (SPECIAL FACTORS)
  - ON ENGINES (PART 33)
    - COMPONENTS WILL NOT BE SUBJECT TO ANY OF ABOVE REQUIREMENTS

- HOW WILL FAA ADDRESS THE ISSUE OF DIFFERENT PART 25 AND PART 33 REQUIREMENTS?
  - CONSIDERATION SHOULD BE GIVEN TO WAIVING SAID REQUIREMENTS FOR PART 25 AM COMPONENTS
    - IN FAVOR OF MEANINGFUL QUALIFICATION & LOT ACCEPTANCE TESTING
      - QUALIFICATION TESTING (FIRST ARTICLE)
        - TO VERIFY ADEQUACY OF MANUFACTURER’S MATERIAL & PROCESS SELECTIONS
      - LOT ACCEPTANCE TESTING
        - TO ENSURE THAT CONFORMING PARTS ARE BEING MANUFACTURED AT ALL TIMES

*(1) FAA ORGANIZATIONS MAY REQUEST REVIEWING THE QUALIFICATION AND LOT ACCEPTANCE DETAILS*
TESTING SHOULD BE PERFORMED ON ACTUAL PARTS-AS AGREED
- CONCURRENT COUPONS Seldom reflect the nature of the component
- Some tests may be performed on concurrent coupons
- There may be situations where parties can agree that
  - Specially designed coupons can be used in lieu of actual parts for lot acceptance testing

As a minimum, the tests should include
- Adhesion verification
- Tensile testing
  - Likely to be performed on concurrent coupons
- Microstructure examination
  - E.g., contamination, porosity, excessive grain growth, unmelted regions, etc.
- Other tests
  - Fatigue, creep, environmental, etc.
    - Concurrent coupons may be required
      - If warranted by the application

There could be situations where functional testing would be required to verify part adequacy
PERSONAL VIEWS, CONTINUED

- I AM NOT IN FAVOR OF INCLUDING AM ALLOWABLES IN THE MMPDS
- THREE REASONS FOR THIS VIEW

1- ALLOWABLES GENERATED FROM SPECIMENS PRODUCED BY A PARTICULAR PROCESS USING SPECIFIC PROCESS PARAMETERS INCLUDING INPUT MATERIALS, AT ONE OR MORE PRODUCTION FACILITIES,
   - SET OF ALLOWABLES COULD BE CONSTRUED AS INTRINSIC TO ALLOY
     - REGARDLESS OF PROCESS, PROCESS PARAMETERS, INPUT MATERIALS OR PRODUCTION FACILITIES
   - SPECIMENS SELDOM REFLECT NATURE OF PARTS PLANNED FOR PRODUCTION

2- PRESENCE OF ALLOWABLES CAN ENCOURAGE UNQUALIFIED AFTERMARKET SUPPLIERS TO WAIVE THE TESTING REQUIRED FOR QUALIFICATION & LOT ACCEPTANCE TESTING AND OFFER LOW QUALITY PARTS AS LOW COST ALTERNATIVES TO OEM PARTS
   - ESPECIALLY IN VIEW OF THE FACT THAT SOME AM EQUIPMENT ARE FAIRLY INEXPENSIVE & READILY AVAILABLE

3- PRESENCE OF ALLOWABLES COULD SERVE AS JUSTIFICATION FOR SOME REGULATING AUTHORITIES NOT TO REQUIRE QUALIFICATION AND LOT ACCEPTANCE TESTING AS PART OF CERTIFICATION SUBMITTALS