ADDITIVE MANUFACTURING IN TURBO-ENGINE APPLICATIONS

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Content

- Introduction
- Additive Manufacturing
  - Laser Metal Deposition LMD
- LMD in Turbo-Engine Applications
  - Demonstrators within the Innovation Cluster “Integrative Production Technology for Energy-Efficient Turbo Machinery” »TurPro«
  - Repair Application – Tip Repair
  - Additive Manufacturing – HPC Blade Mock-up
- Further Examples
- CAD/CAM Module
- Conclusions and Outlook
Turbo-engines

- **Turbo-engines (gas turbines, steam turbines, compressors)**
  are continuously working energy conversion machines. Depending on the direction of the conversion they are differentiated into power machines and work machines.

- **Power machines**
  convert thermal energy into kinetic energy (work). A typical example is a turbine.

- **Work machines**
  use kinetic energy and produce electricity or are used for transporting or compressing solids or gases. Examples are compressors, pumps and blowers.
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Laser Metal Deposition LMD with powder feeding

Source: TRUMPF
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Fraunhofer Cluster of Innovation »TurPro«

»TurPro«
Integrative production technology for energy efficient turbo machines

- Manufacturing and repair processes for compressor and turbine components
- Industries: Power Gen & Aerospace
- Budget: 10.25 Mio. €
  - Industry: 3.1 Mio. €
  - Fraunhofer: 4.05 Mio. €
  - NRW: 3.1 Mio. €

Partners:

Granted by North Rhine-Westphalia
Process-chain for Repair – Tip Repair

Process-chain for: GT-Blade

- Integrated software platform
- Integrated clamping system

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Cluster L
Process Development

- LMD of blade crown:
  - Web width 1,2 mm
  - Web height 5,0 mm

- Material:
  - Blade: 1.4313 [X3CrNiMo13-4]
  - Powder: 1.4313, grain size 45 - 75 µm

- Requirements:
  - Low / no distortion
  - Pores allowed ≤ 50 µm
Cluster L
Process Development

Input

- Input from Cluster C:
  - CAx-Cluster: NC-programmes for Clusters M and L

- Input from Cluster M:
  - Oversize for milling: 0.3 mm on each side
    ⇒ width of web ≥ 1.8 mm
  - Height of web 5.5 mm
  - Milling results from mock-ups

- Input from Cluster L:
  - Process strategy
  - Mock-ups for developing milling strategy
Cluster L

Process Development

Min. web width: 1,4 mm
Max. web width: 1,9 mm
Waviness: 0,12 mm

Layer N
Layer N+1

450 mm/min
550 mm/min

Starting point: constant parameters → adaptation
Adaptation of parameters
All requirements fulfilled
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Partners:

Additive BLISK manufacture

Granted by North Rhine-Westphalia
## Motivation

### Today's BLISK production
- Milling from solid
- ECM
- Linear friction welding of blades onto disks

### Disadvantages:
- Time and material consumption
- Restricted geometries

### Vision: BLISK production in the future
- Direct production with LMD
- Near net shape
- Adaptive milling for finishing

### Potentials:
- Time reduction
- Material consumption reduction
- Complex geometries / material combinations
- Economic efficiency?
Motivation

**Now**

- Suitable for large area wear protection
- Suitable for repair

**Future**

- Small track width and high deposition rates
- Adjustment of track width during process
- Suitable for near net shape production
Fields of expertise for process development

- Zoom optics, Near-net-shape
- Systems engineering

Appropriate process windows &
process layout (CAD/CAM)

Static and dynamic
mechanical properties

Materials

Beam source(s)

Disk laser, 1 µm, 10 kW

Process fundamentals
Significantly increased cooling rates

→ Influence on micro and macro structure

100 µm
Experimental Set-up

- Yb:Yag 10 kW Disk Laser
- Inconel 718 powder
- ILT 3-beam nozzle
- powder gas stream
- melt pool
- work piece
- shielding gas
- zoom optic
- collimation lens
- Trumpf Laser Cell
- powder feeder
Experimental Procedure IN 718

- LMD of single tracks with high deposition rate
  - For overlapping structures
  - For blade root

- LMD of webs with high deposition rate
  - For filigree web structures
  - For blade
LMD Graph

- Includes all relevant processing parameters
- Information about porosity and powder efficiency
- Illustrates suitable parameter windows
- Can be used as a tool for process development

The diagram shows a parameter window on a graph with axes for laser power, scanning speed, and powder mass flow. The graph illustrates the maximum available power (10 kW), maximum tool velocity, and the maximum powder flow rate for a 3-jet nozzle. The parameter window highlights the areas with dimensional accuracy and bonding defects, as well as the information about porosity and powder efficiency. This tool can be used for process development.
LMD Graphs for Single Tracks

4 mm tracks

2 mm tracks

before
LMD Graphs for Single Tracks

- Deposition rate for 2 mm track width:
  
  \[3615 \text{ mm}^3/\text{min} \ (1.78 \text{ kg/h})\]

- Deposition rate for 4 mm track width:
  
  \[8655 \text{ mm}^3/\text{min} \ (4.25 \text{ kg/h})\]

- Deposition rate for 1.5 mm track width before increasing the deposition rate:
  
  approx. 200 mm\(^3\)/min (0.1 kg/h)
LMD Graphs for Webs

![Graph showing laser power vs. scanning speed for 2 mm and 4 mm webs](image)

- **4 mm webs**
  - Laser power [W]
  - Scanning speed [mm/min]
  - Porosity: (0% - 0.1%)
  - Porosity: (0.1% - 0.25%)

- **2 mm webs**
  - Laser power [W]
  - Scanning speed [mm/min]
  - Porosity: (0% - 0.1%)
  - Porosity: (0.1% - 0.25%)

**Legend**
- Green circles: Porosity (0% - 0.1%)
- Yellow diamonds: Porosity (0.1% - 0.25%)

**Note:**
- The graph shows the relationship between laser power and scanning speed for different web thicknesses, illustrating how porosity varies with these parameters.
LMD Graphs for Webs

- Deposition rate for 2 mm webs: 5939 mm³/min
- Deposition rate for 4 mm webs: 9262 mm³/min
- Powder efficiency:
  - for 2 mm webs > 60%
  - for 4 mm webs > 80%
LMD of Cuboids with Increased Deposition Rate

1. η > 60%
2. η > 70%
3. η > 80%

η = powder efficiency

4 mm tracks

2 mm tracks

Laser power [W]

Scanning speed [mm/min]

Powder mass flow [ppm]

1. t=1s V=5.7 mm³
2. t=1s V=104 mm³
LMD of Near-net-shape HPC Blade Mock-up

Aim:
Increase of economic efficiency:
- Build-up of Mock-up blade by LMD
- Milling of blade
- Maximum deposition rate for LMD (process time)
- Over measure (1 mm -1,1 mm)

HPC FRONT DRUM HCF TEST SPECIMEN
(Source: Rolls-Royce Deutschland)
LMD of Near-net-shape HPC Blade Mock-up

Blade base:
- Track width \( d_L = 4 \) mm
- Speed \( v_V = 2000 \) mm/min
- Layer height \( d_Z = 1.65 \) mm

HPC FRONT DRUM HCF TEST SPECIMEN
(Source: Rolls-Royce Deutschland)
LMD of Near-net-shape HPC Blade Mock-up

Blade base:
- Track width $d_L = 4 \text{ mm}$
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HPC FRONT DRUM HCF TEST SPECIMEN
(Source: Rolls-Royce Deutschland)
LMD of Near-net-shape HPC Blade Mock-up

Strategy for blade build-up

Support points

Layer n+1
Layer n
Start-/End

HPC FRONT DRUM HCF TEST SPECIMEN
(Source: Rolls-Royce Deutschland)
LMD of Near-net-shape HPC Blade Mock-up

- Build-up of Mock-up blade in t< 2 min (near net-shape)
Near-net-shape additive manufacturing of HPC blades

- Strategy development for additive manufacturing of BLISKs
LMD of Near Net-shape HPC Blade Mock-ups

1. LMD Process strategy development
2. LMD CAx implementation
3. Geometry data acquisition
   - Machining

Feedback

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Near-net-shape build-up of BLISK blade mock-ups

- Joint process strategy development @ IPT/ILT
- Implementation of process layout in CAx-framework
- Oversize (-0.05 – (+) 1.2 mm) by LMD

Finish machining
Pre finish machining
Rough machining
LMD

Adaptation of NC strategy and improvement of clamping
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Examples LMD: NGV 2 (+ Liner 1)

LMD of mesh structures, In 625 on Mar-M 002 (+ CMSX-4)

NGV 2 with LMD mesh structures

Liner 1 with LMD mesh structures
Reconditioning of damping wire grooves / Ti6246

Main challenges:
- Accessibility
- Processing without affecting opposite wall

In cooperation with Rolls-Royce Deutschland
LMD of aero engine components at KLM, Amsterdam

Examples: housing flange (Inconel 718), rotating seals (17-4PH)

In cooperation with KLM
Repair of Compressor and Steam Turbine Components

Radial compressor

Axial compressor

Steam turbine shaft

LMD of bearing areas of shafts from radial and axial compressors and steam turbines

Source: MAN Diesel & Turbo SE
Repair of Compressor and Steam Turbine Components

Source: MAN Diesel & Turbo SE
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Further Examples

CAD/CAM Module

Conclusions and Outlook
Requirements LMD CAM module for repair

Starting point for repair:

- Machining of damaged area (automated / manual)
- Laser scanning of machined area
- Description of scanned surface as polygon-net
- Description of boundaries of area to be processed with master geometry

- Geometry core of CAM Module should address polygon-net, with a typical size of $10^6$ triangles coming from the laser scanning data
- Generation of equidistant (not projected) tool paths on free-form surface, with trimming at given boundaries
- Trimming of superposed layers based on master geometry
Requirements LMD CAM module for additive manufacturing

Starting point for additive manufacturing:

- Feature (e.g. blade) is built on free-form surface
- LMD boundaries in upper layers are given from intersection of build-up surface with feature to be built-up

- Core of CAM module should address intersections of two arbitrary free-form surfaces
CAM Module LaCam3D

1) Boundary (intersection build-up surface with blade geometry)
2) Center line
3) Tool path in the layer: equidistant tracks on build-up surface trimmed with boundary

Geometry core is capable to produce tool path for layer wise build-up in additive manufacturing and in repair
Choice of strategy (uni- / bidirectional, sequence, direction, hatching, contour)
Automatic trimming of subsequent layers on master geometry
CAM Module LaCam3D

- Simulation tool for collision
- Adapted post processor for the generation of CNC codes
CAM Module LaCam3D

- CAM module for the generation of tool paths including complex tool paths for additive manufacturing with LMD
- Can use stl data from laser scanners, no need of surface description via nurbs
- 3 axis version available and in usage at ILT since 1 year
- In testing phase at two customers
- 5 axis version under development
- Open for implementation of additional component specific LMD strategies

Live presentation this afternoon at ILT
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Conclusion and Outlook

- Laser Additive Manufacturing (LAM) offers huge potential for turbo-engine components
- Laser Metal Deposition (LMD) is already used for the repair of many components
- Increase of deposition rate in LMD by a factor of 40 has been achieved
- New CAD/CAM module LaCam3D

Outlook:
- Challenging materials (higher γ’ contents, Inconel 738, SX alloys, …)
- Further qualification of new components for LMD (optics for variable track size, inside LMD, …)
- Process monitoring / control for quality assurance
Acknowledgement

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- Granted by

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