Advanced Manufacturing for the Gas Turbine Platform

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LAMP™ and SLE™ - Advanced Manufacturing Technologies for Turbine Engine Hot-Section Components

Direct Digital Manufacturing and Remanufacturing of Turbine Engine Components

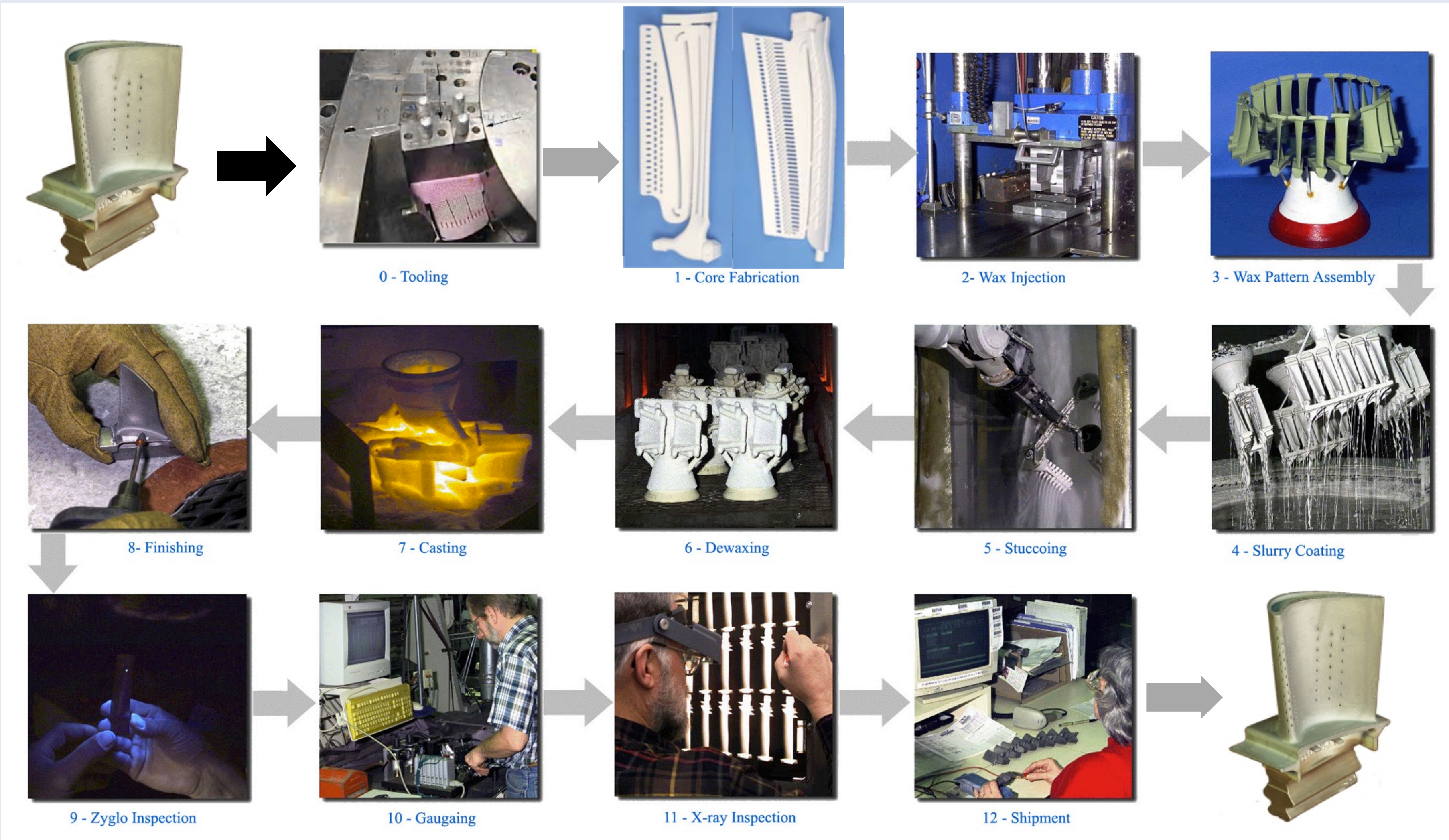
LAMP™ - Large Area Maskless Photopolymerization

- Digital 3-D printing of ceramic cores and integral cored molds.
- Disrupts conventional investment casting.
- Foundry compatible.
- No change to conventional metallurgy.
- Eliminates variation.
- Enables advanced cooling designs.
- Enables breakthrough efficiencies.

SLE™ - Scanning Laser Epitaxy

- Disruptive direct metal additive manufacturing and repair
- Processing of non-repairable and non-weldable hot-section nickel-base superalloys.
- Repair and refurbish fielded engine components to "as good as new" or "better than new".
- Produce functional fully dense, 3-D components from metal powders.
- Enables surge production.

State of the Art of Manufacturing Hot-Section Components Through Investment Casting



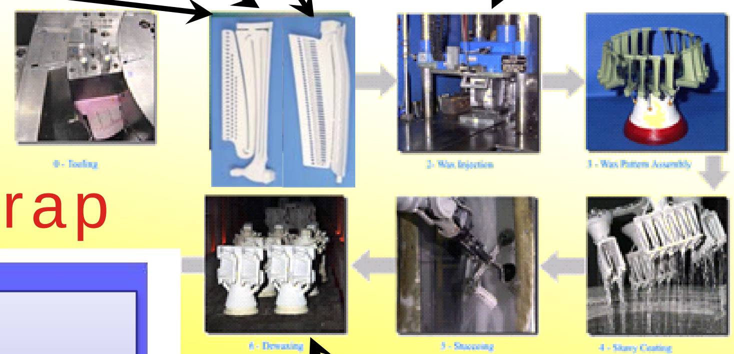
Scrap, Cost and Lead Time in Precision Investment Casting

Core Assembly:
- Handling breakage
- Variability breakage
- Hand finishing breakage
- Glue joint failures

Core firing
- Firing Distortion
- Core shift
- Glue joint failure
- Handling breakage

Wax injection
- Core shift
- Glue joint failure
- Core breakage

Core Fabrication
- Ejection breakage
- Handling breakage
- Die Wear
- Dimensional variability



De-Waxing
- Core breakage

90% of Scrap

Casting
- Core sag/slump and shift (kiss-out, mis-run)
- Glue joint failure
- Recrystallized grain

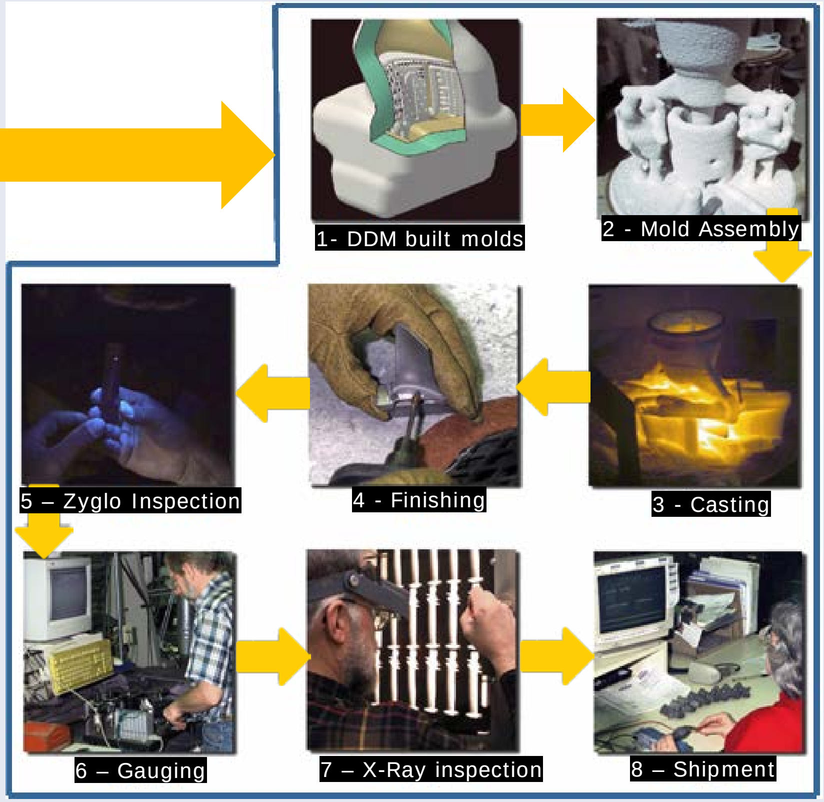
Further 6% Scrap

DIRECT DIGITAL MANUFACTURING OF INVESTMENT CASTINGS THROUGH LARGE AREA MASKLESS PHOTOPOLYMERIZATION (LAMP)

Cutaway view of ICM design

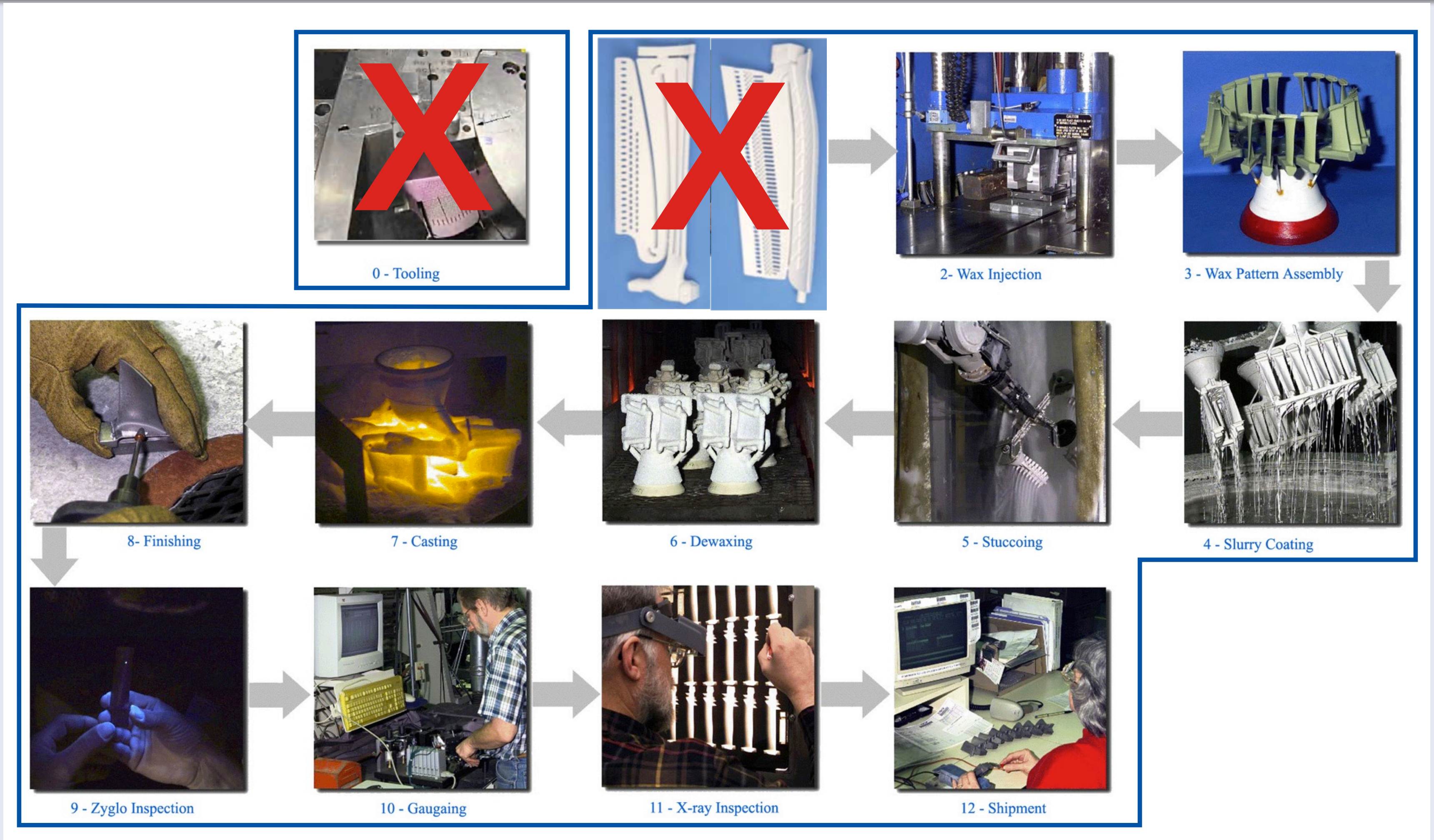
High resolution bitmaps of CAD slices

Large Area Maskless Photopolymerization (LAMP)



Airfoil investment casting process with direct digital manufacturing

Impact of LAMP on Core Manufacturing



Figures Courtesy of Howmet Castings

- Over 2 major processes and all core injection tooling eliminated.
- All digital fabrication eliminates variation, enables tighter tolerances and reproducibility.
- Rapid design changes, rapid prototype iterations, and rapid manufacturing enabled.
- Advanced design concepts easily prototyped and incorporated for production.

Impact of LAMP on Integral-Cored Shell Mold Manufacturing

Figures Courtesy of Howmet Castings

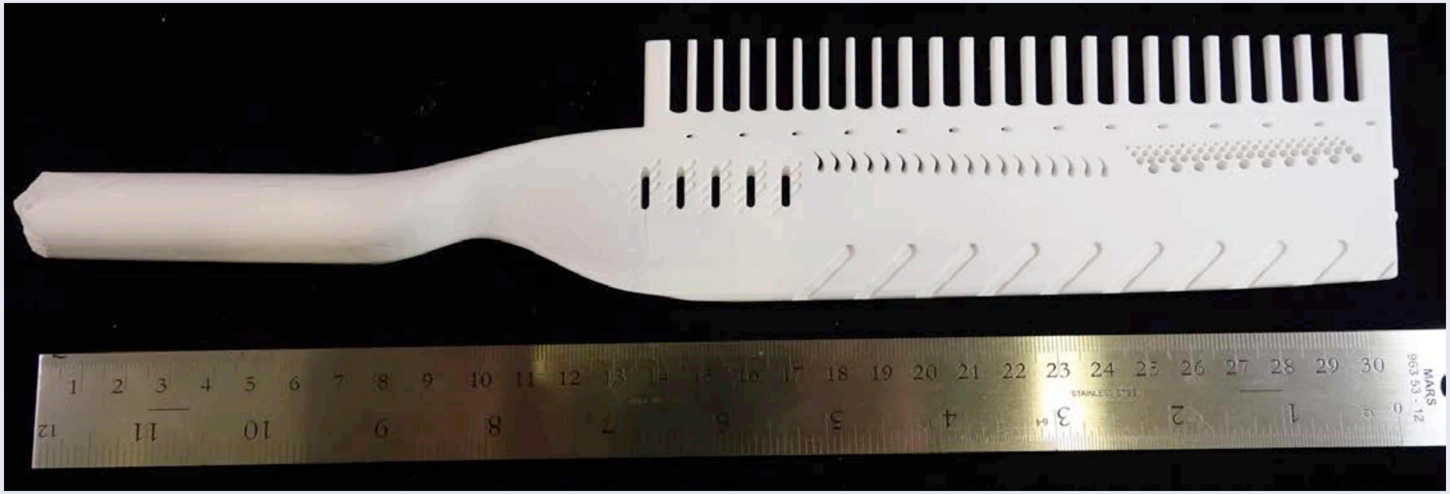
- Over 7 major processes, and wax patterns, and all core and wax injection tooling eliminated.
- All-digital fabrication enables manufacture of engineered cores and shell molds with advanced design features previously considered very difficult or impossible to make.
- Same material for core and shell eliminates thermal expansion mismatch.

Impact of Direct Digital Investment Casting Through LAMP

- **64% cost reduction**
- **66% cycle time reduction**
  - Model to metal in 4 vs. 12 weeks
  - WIP Inventory reduced by 8 weeks
- **97% tooling cost reduction**
  - Switching cost to a new supplier is dramatically reduced.
  - Dual sourcing becomes an affordable option.
- **100% tooling cycle time reduction**
  - Can eliminate up to 2 years in airfoil production schedule
- **90% scrap reduction**
  - Hand finishing – Eliminated
  - Core handling – Eliminated
  - Core assembly – Eliminated
  - Glue joints – Eliminated
  - Wax Injection – Eliminated
  - De-Waxing – Eliminated
- **Dramatically improved producibility**
  - Improved positional stability
  - Reduced sag, slump, and shift
  - Enabled complex geometries, e.g., backlocked, complex internal 3-D curved cooling passages

LAMP State of the Art

LAMP-Manufactured Generic Aviation Airfoil Core and Integral-Cored Shell Mold

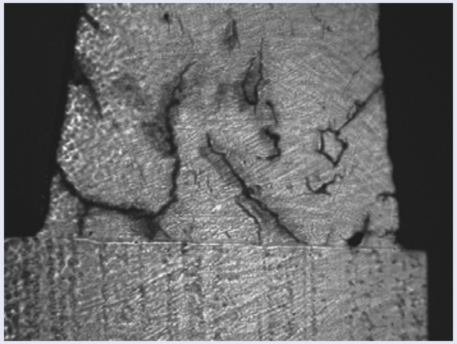


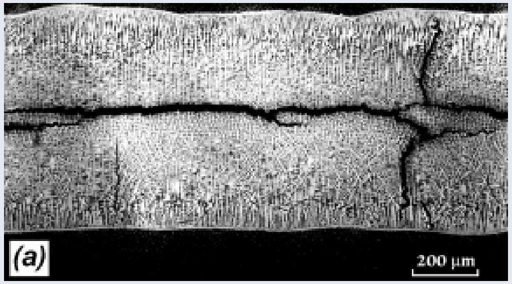
LAMP-Manufactured Generic Industrial Gas Turbine Blade Core Segment

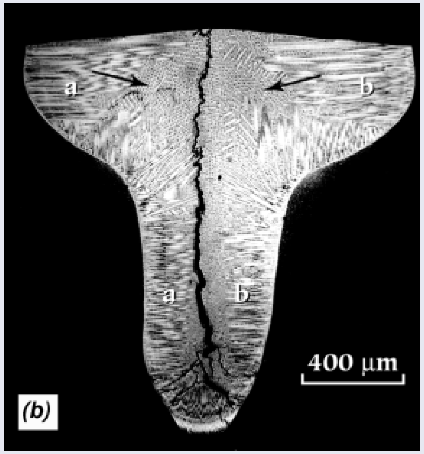
Turbine engine hot-section components are made of non-weldable alloys that are highly crack prone making their weld processing very challenging

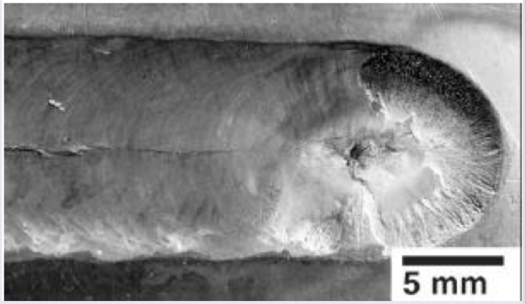
<u>Processing Challenges</u>

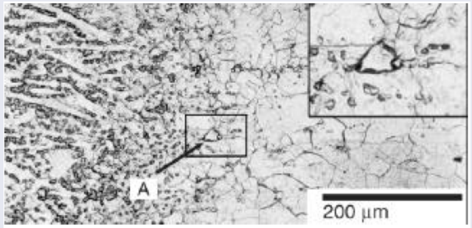
- Solidification Cracking/Hot tearing.
- Grain Boundary Liquation Cracking.
- Strain Age Cracking.
- Recrystallization and Loss of Underlying Microstructure.
- Preserving nominal alloy composition.
- Tramp elements in alloy composition.
- Oxidic cleanliness and impact on properties.
- Powder contamination.
- Unmelted powder particles trapped in the melt.

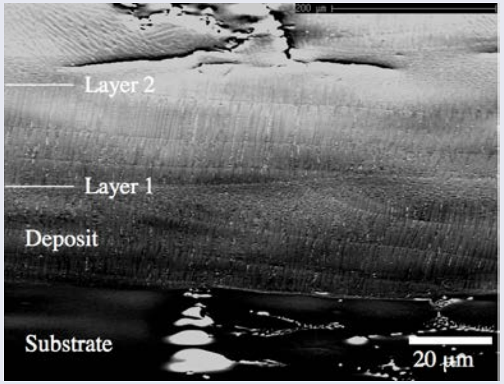




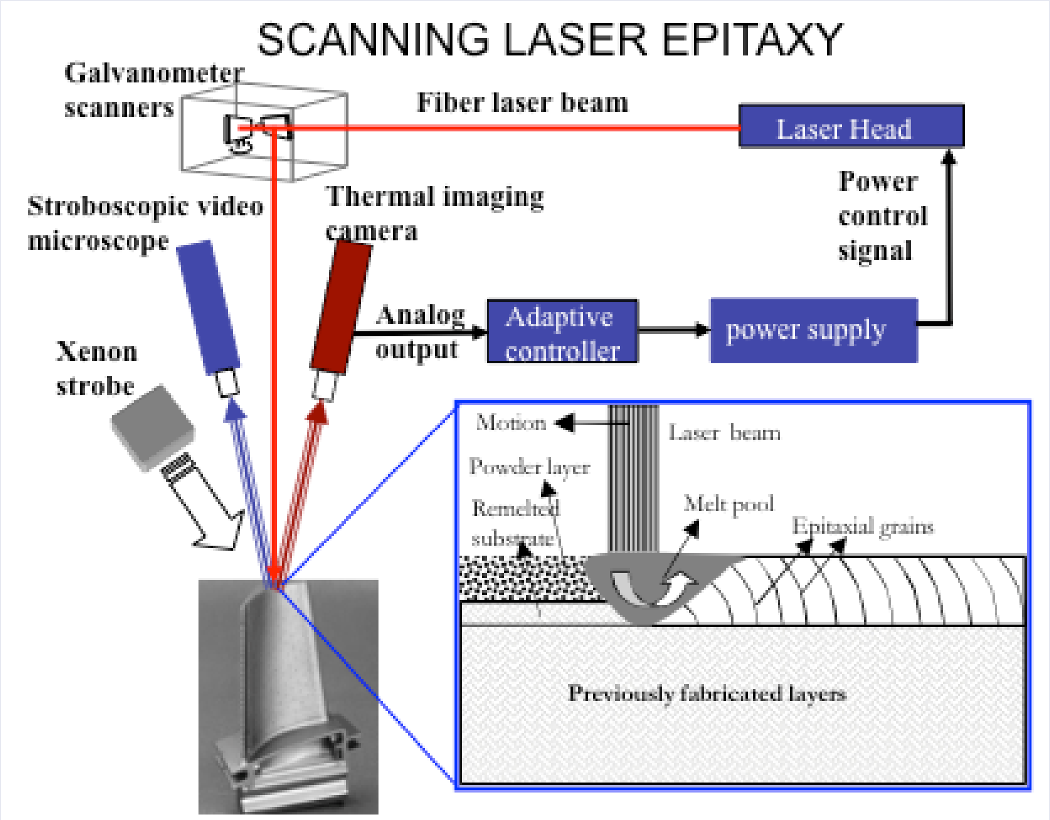








Direct Digital Manufacturing and Repair of Turbine Engine Hot-Section Components Made of Non-Weldable Alloys Through Scanning Laser Epitaxy (SLE)



Additive Repair of Turbine Components

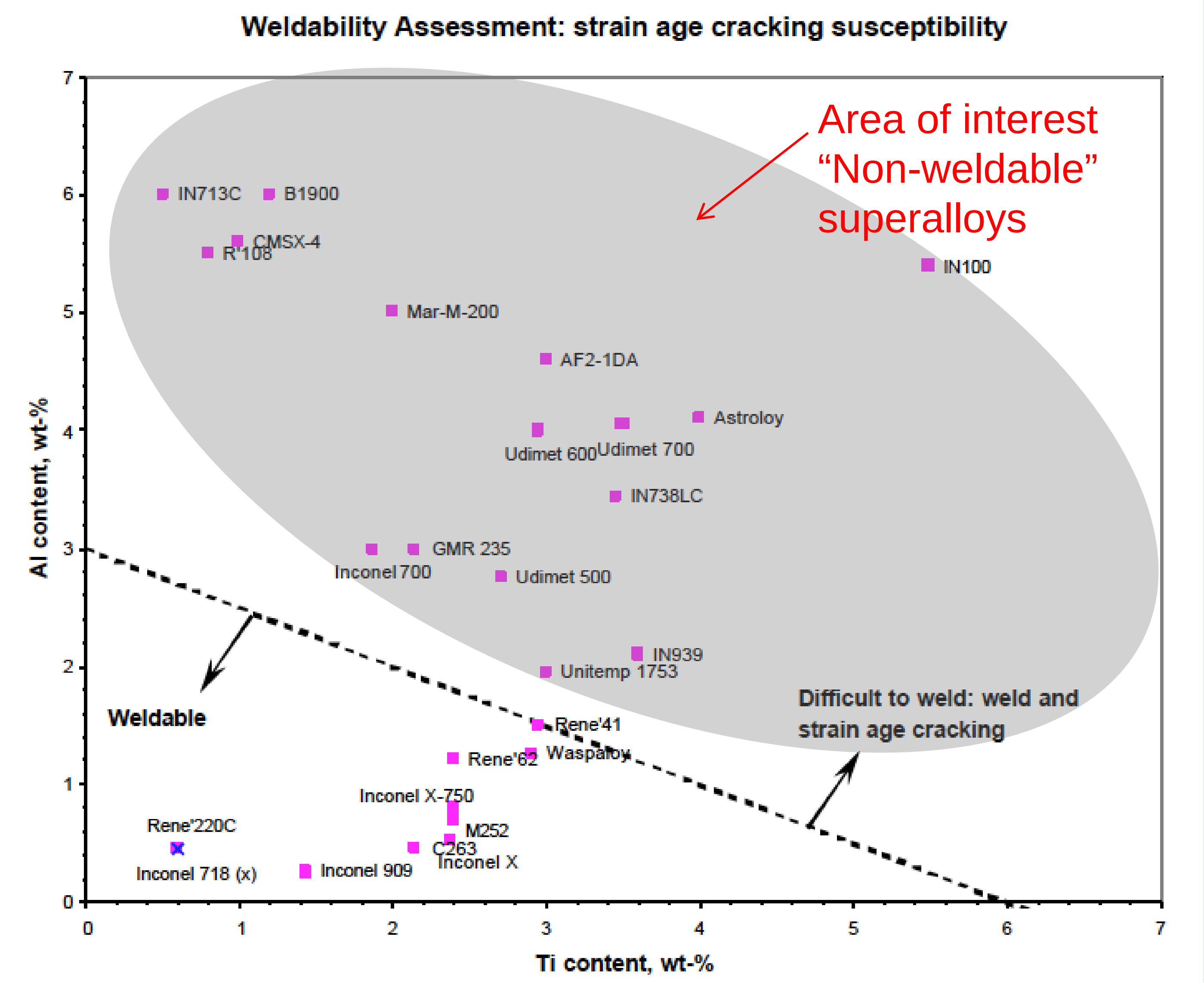
- Repair technology for non-weldable or non-joinable superalloys including equiaxed, DS and SX.
- Repair of manufacturing defects on surfaces: Porosity, hot tearing, inclusions, misruns.
- Repair of aging stationary and rotating engine components.

Additive Manufacturing of Turbine Components

- Apply the learnings from repair to metal-powder bed-based layer-by-layer 3-D additive manufacturing.
- Produce fully dense, defect free components without tooling or post-processing.
- Process advanced material systems considered extremely difficult or expensive conventionally.
- Functionally graded structures.

SLE Alloy Process Development Prioritization Approach

- ✓MARM-247
- ✓CMSX-4
- ✓Rene N5
- ✓Rene 80
- ✓Rene 142
- ✓IN 100
- ❑ PWA 1480
- ❑ PWA 1484
- ❑ GTD 111
- ❑ Rene 108
- ❑ Rene 220
- ❑ CM 247 LC
- ❑ IN 713
- ❑ IN 738
- ❑ IN 738 LC



SLE Applications Two-Step Development Approach

Additive Repair of Turbine Components

- Develop repair technology for non-weldable or non-joinable superalloys including equiaxed, DS and SX.
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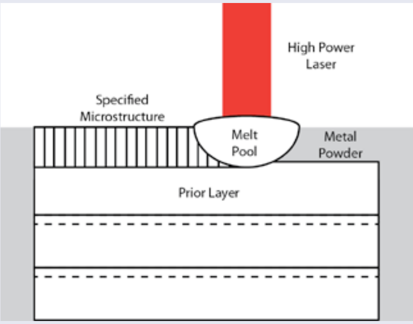
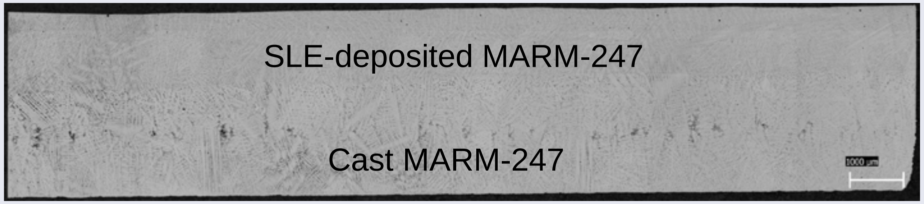
Additive Manufacturing of Turbine Components

- Apply the learnings from repair to metal-powder bed-based layer-by-layer 3-D additive manufacturing.
- Produce fully dense, defect free components without tooling or post-processing.
- Process advanced material systems considered extremely difficult or expensive conventionally.
- Produce functionally graded components that are currently difficult to manufacture.

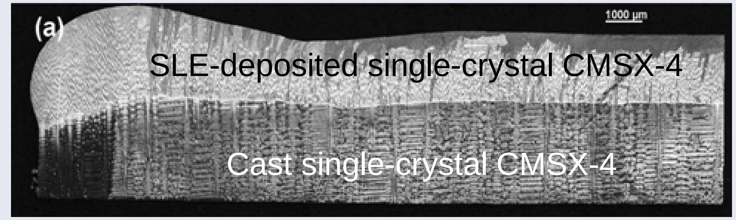


SLE Applications Two-Step Development Approach

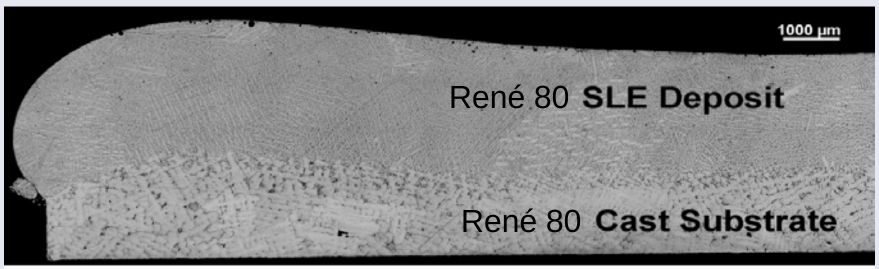
Single Pass SLE Deposition of Hot-section Alloys onto Like-chemistry Substrates



Equiaxed MARM-247 on cast MARM-247



SX CMSX-4 on cast SX CMSX-4



Equiaxed René 80 on cast René 80

Equiaxed René 142 on cast Rene 125

Equiaxed IN 100 on cast IN 100

SX René 142 on cast SX René N5 [001] and [100]

Conclusions

- LAMP technology is on the path to disrupting state-of-the-art of investment casting and technical ceramics through tool-less additive manufacturing.
- SLE technology is on the path to disruptive state-of-the-art of additive manufacturing of “non-weldable” turbine engine hot-section alloys and other “difficult to process” high temperature materials.
- DDM Systems is commercializing both technologies under exclusive license from Georgia Tech with commercial systems and optimized materials entering the market in 2015.

Disclosure

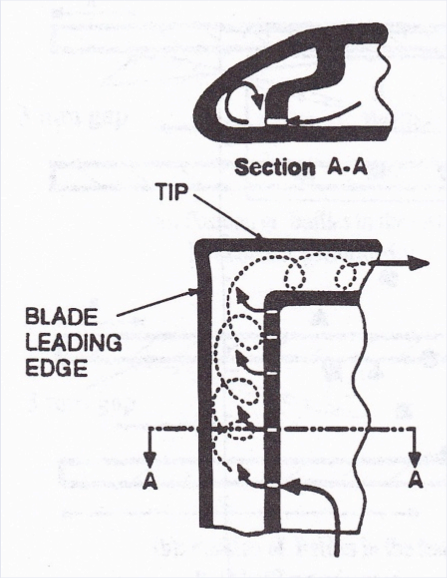
DDM Systems, a startup company co-founded by Dr. Suman Das, is commercializing LAMP™ and SLE™ technologies under an exclusive license from the Georgia Tech Research Corporation.

Dr. Suman Das and Georgia Tech are entitled to royalties derived from DDM Systems' sale of technologies and products described in this presentation. The terms of this arrangement have been reviewed and approved by Georgia Tech in accordance with its conflict of interest policies.

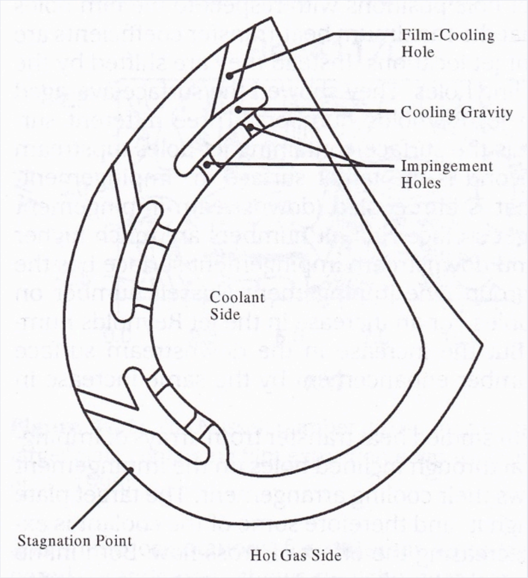
Further information on DDM Systems is available at:

http://ddmsys.com

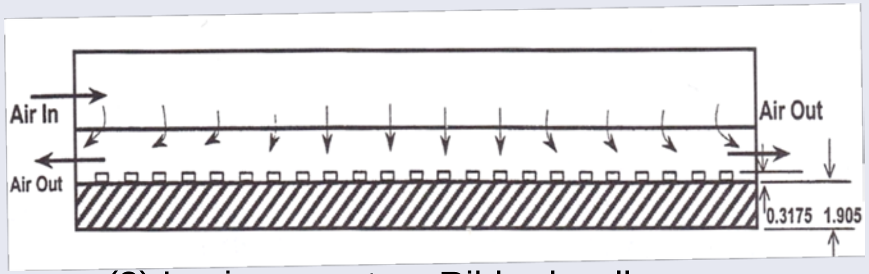
Novel Leading Edge Cooling Structures Possible



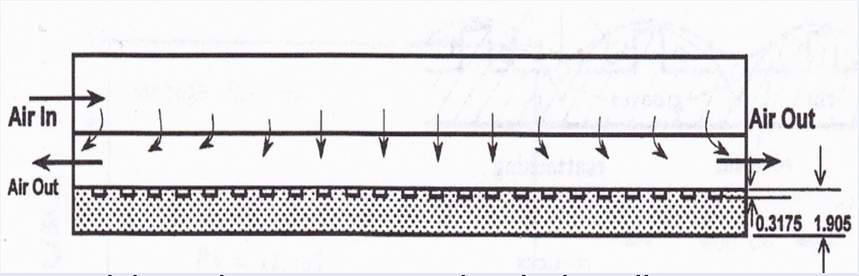
(1) Modified Impingement chamber that produces “screw” shaped flow path



(2) Cooling Cavities and Film cooling air exit



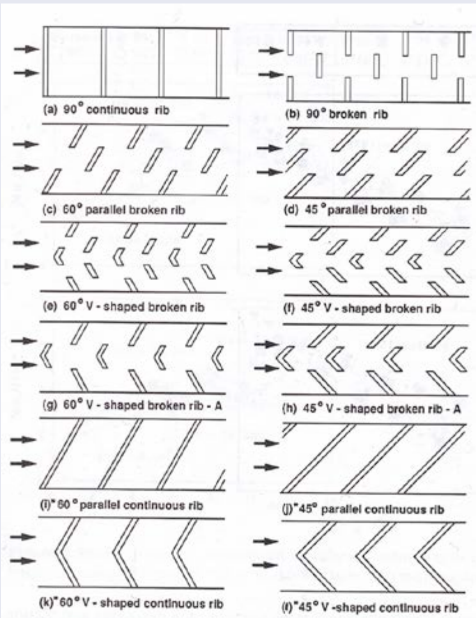
(3) Impingement on Ribbed wall



(2) Impingement on Dimpled Wall

Gas Turbine Heat Transfer and Cooling Technology, Han, Dutta and Ekkad, Taylor and Francis, 2000.

Novel Mid-Chord Cooling Structures Possible



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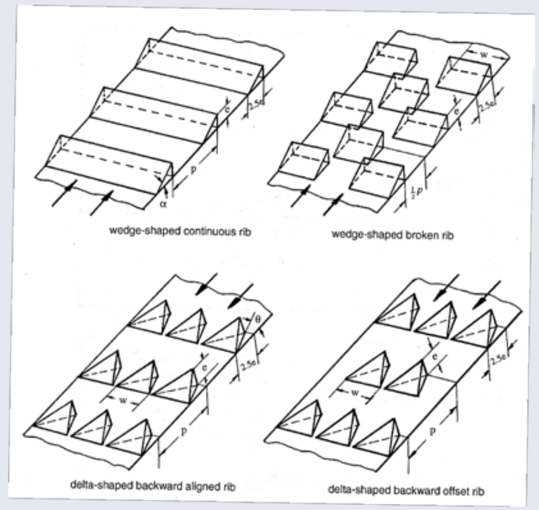

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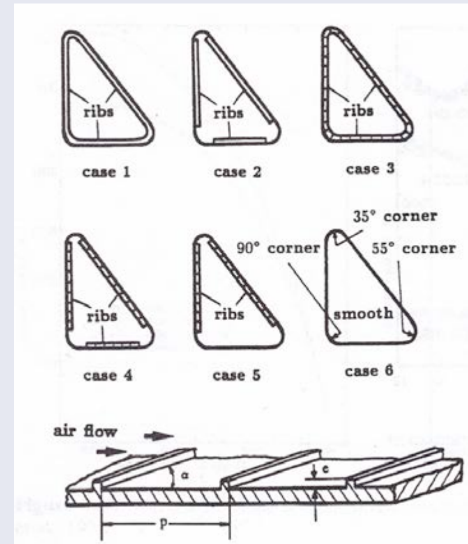

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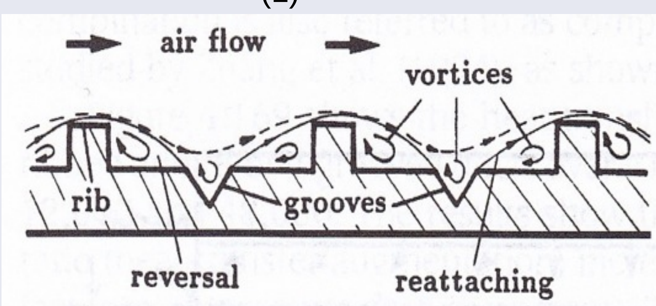
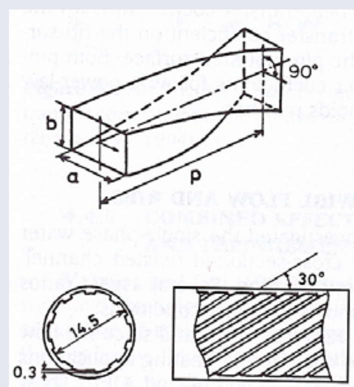


(4)

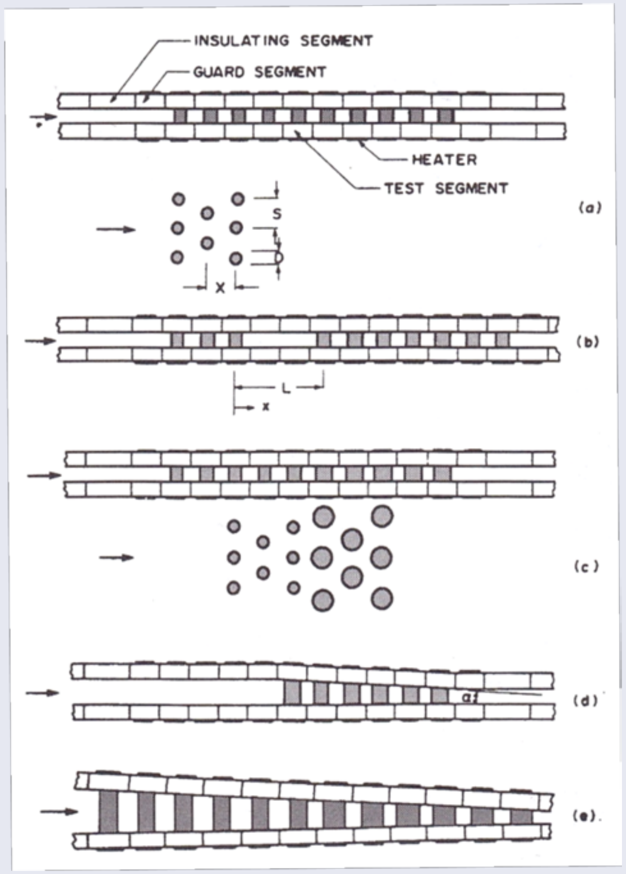


(5)

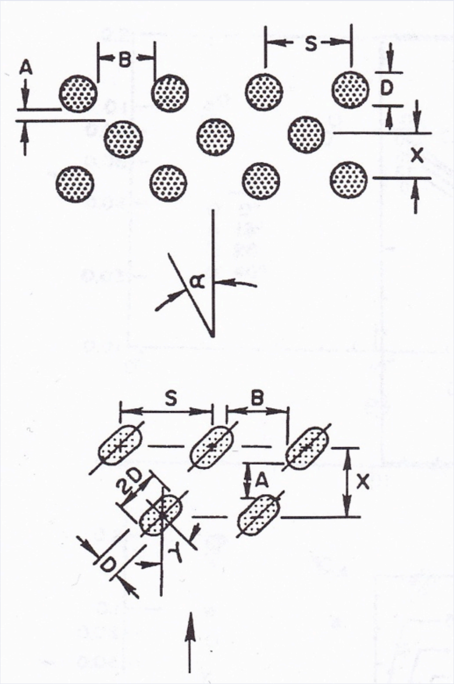
1. Novel Rib Turbulator configurations inside cooling channels
2. Novel Rib Shapes and arrangements
3. Triangular channel with inclined ribs
4. Ribs along with V-groves
5. (Top): Swirling Rectangular channel(Bottom): Round channel with spiral ribs

Gas Turbine Heat Transfer and Cooling Technology, Han, Dutta and Ekkad, Taylor and Francis, 2000.

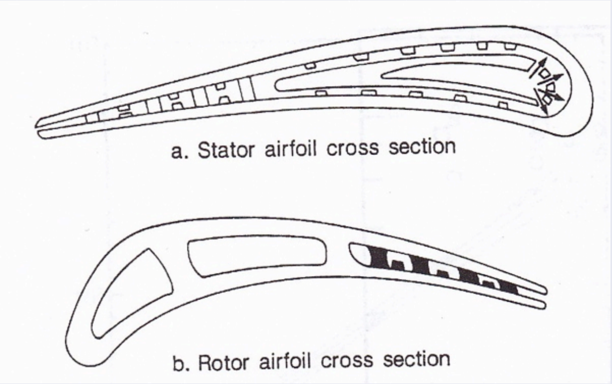
Novel Trailing Edge Cooling Structures Possible



(1) Non Uniform Pin fin distribution with various diameters and converging angles



(2) Skewed Configurations for round and oblong pins



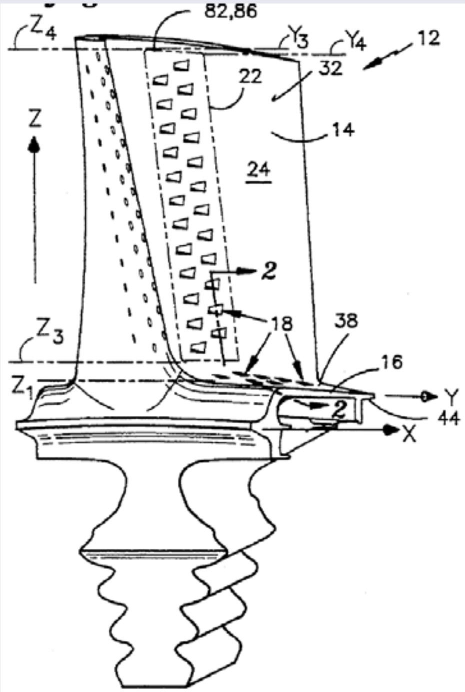
(3) Partial pins for augmented cooling

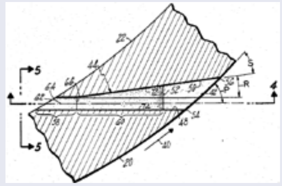
Payoff

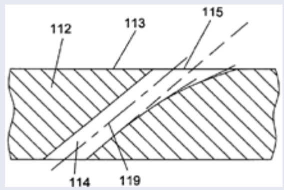
- Scope for implementing novel cooling features constrained by manufacturability is huge.
- Coupled with heat transfer and fluid flow analysis, LAMP can be a potential tool for extending the scope of manufacturing conventionally non-manufacturable high efficiency designs.

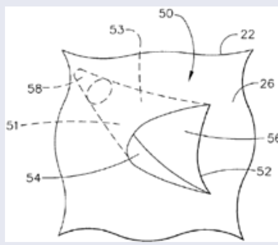
Gas Turbine Heat Transfer and Cooling Technology, Han, Dutta and Ekkad, Taylor and Francis, 2000.

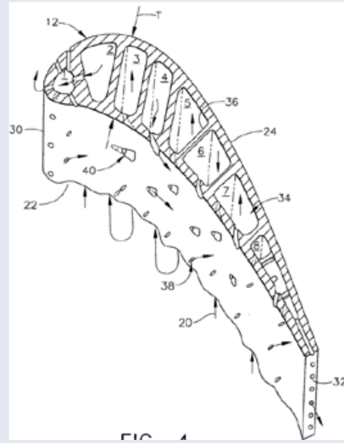
Film Cooling and External Cooling

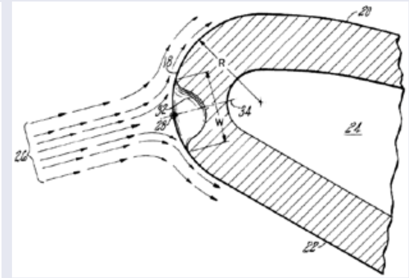


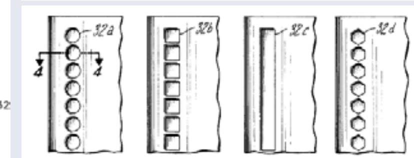


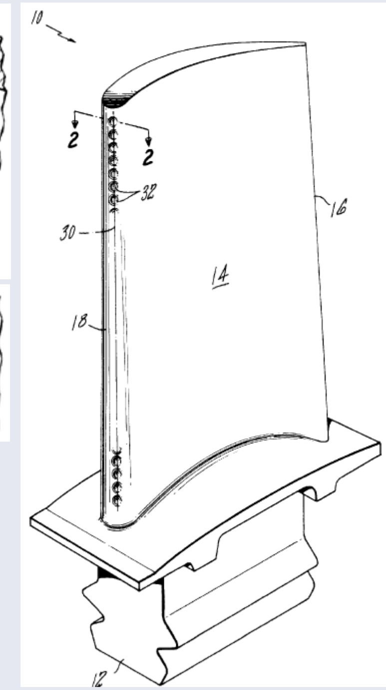












Auxier et al., US Patent 4,664,597
Adamski, US Patent 5,418,34
Lang, III et al., US Patent 6,139,258
Palmer et al., US Patent 7,249,934
Lee, US Patent 7,374,401
Liang, US Patent 7,887,294

Payoff

- Scope for implementing novel cooling features constrained by limitations of conventional manufacturing is vast.
- Coupled with heat transfer and fluid flow analysis, LAMP can be a potential tool for extending the scope of manufacturing conventionally non-manufacturable high efficiency designs.
- Cost and lead time of prototyping advanced cooling designs is dramatically reduced.