State of the Art in Additive Manufacturing and Lightweighting Design of Internal Combustion Engine & Parts

Presenter： Jikai Liu

SHANDONG UNIVERSITY
1901

Outline:

1. Background Introduction
2. Lightweighting Design of Internal Combustion Engine & Parts
3. Advanced Manufacturing of Internal Combustion Engine & Parts

Motivation of Lightweighting Design

- Lightweighting design of high-end equipment is highlighted in ‘Made in China 2025’.
- Passenger cars in China weigh 8%~10% higher than cars of the same class in Europe. Business cars weigh 10%~15% higher[1].
- When the car weight reduces by 10%, fuel consumption decreases by 8% and the emission reduces by 4%[1].
- Internal combustion engine occupies 12% of the total weight of passenger cars[1].

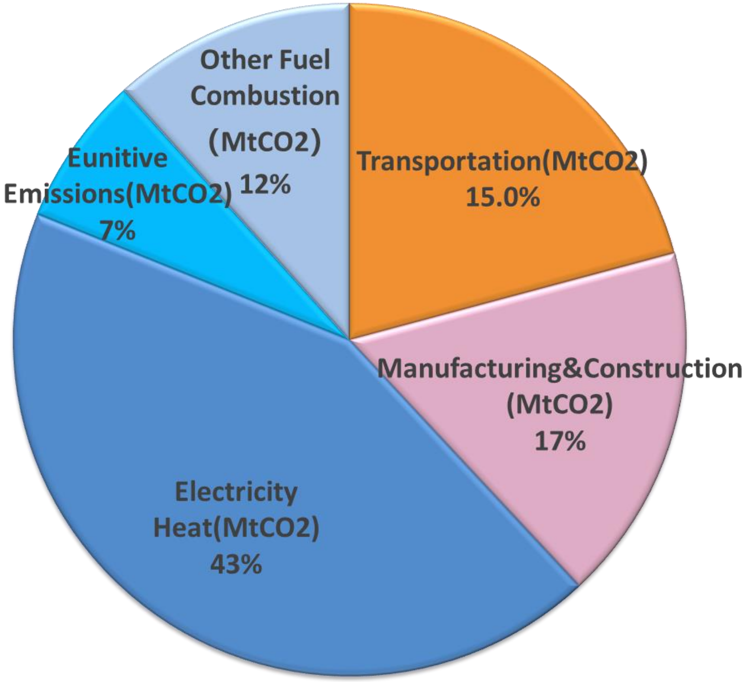


Fig. 1 Global Manmade Greenhouse Gas Emissions by Sector[2]

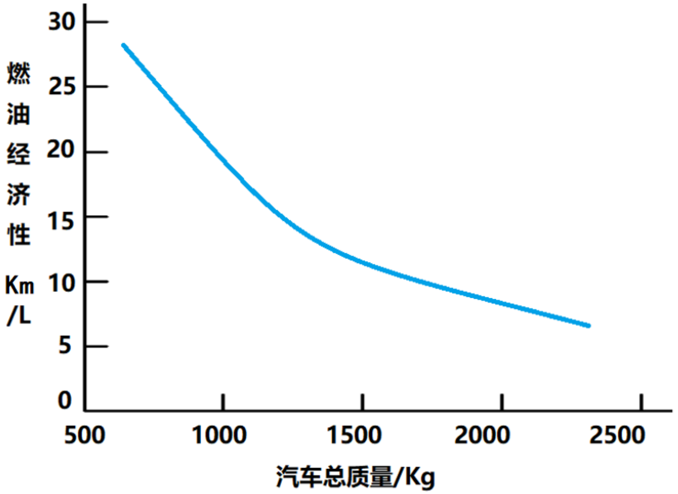


Fig. 2 Relationship between the car weight and fuel consumption

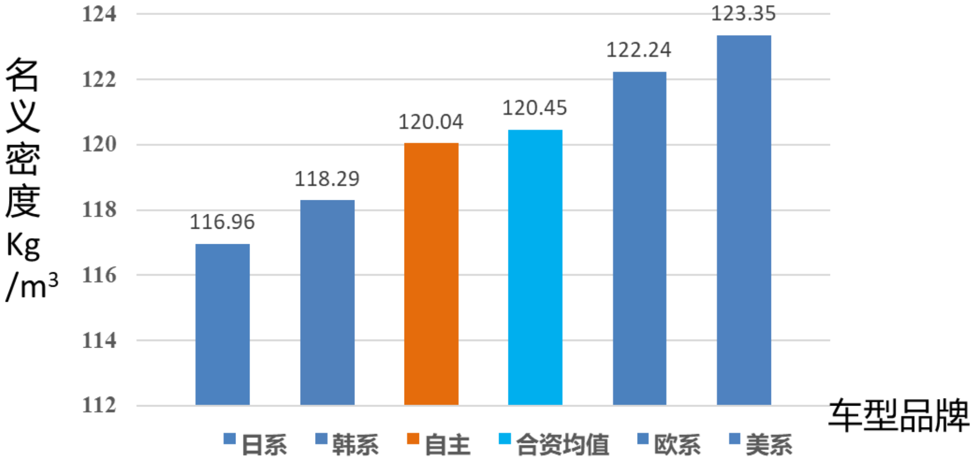


Fig. 3 Lightweighting performances of passenger cars from different countries

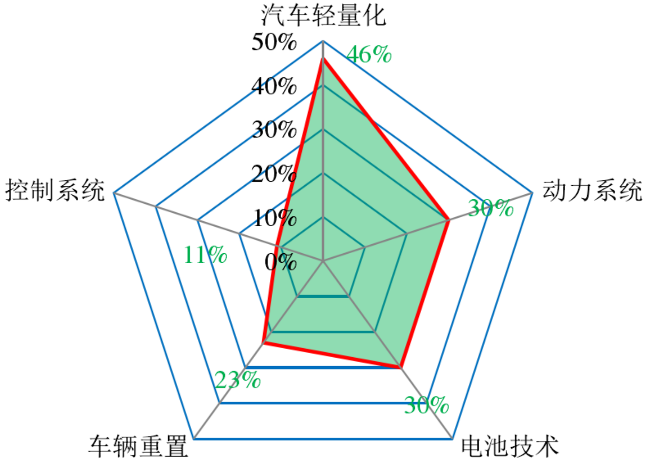


Fig. 4 Potentials of different techniques on energy saving[3]

Approaches for Lightweighting Design

(1) New materials: High strength steel, aluminium, magnesium alloys, and other non-metallic composites.
(2) Structural optimization: Generative design through topology optimization.
(3) Advance manufacturing technology

Fig. 5 Lightweighting through internal high pressure forming[4]

Fig. 6 Lightweight material for the car body[5]

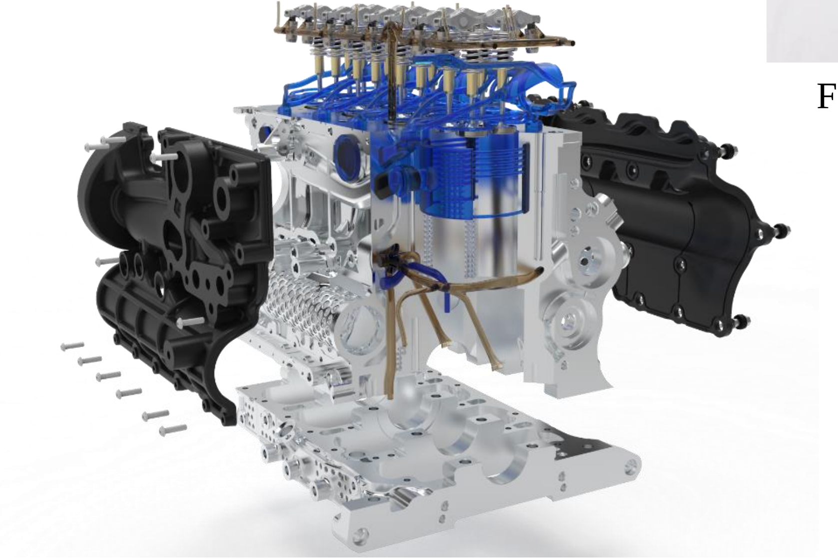


Fig. 7 FEV “LeiMot” efficiency boosting lightweight engine (21% weight reduction, cylinder head 2.1kg, crankcase 5.1kg)

Fig. 8 Lightweighting through structural optimization[6]

Topology Optimization

Topology optimization is an algorithmic process that reveals the most efficient design based on a set of constraints or characteristics, often by removing material from the design.

Improve strength-to-weight ratios by removing excess material that is not necessary for the design's performance requirements.

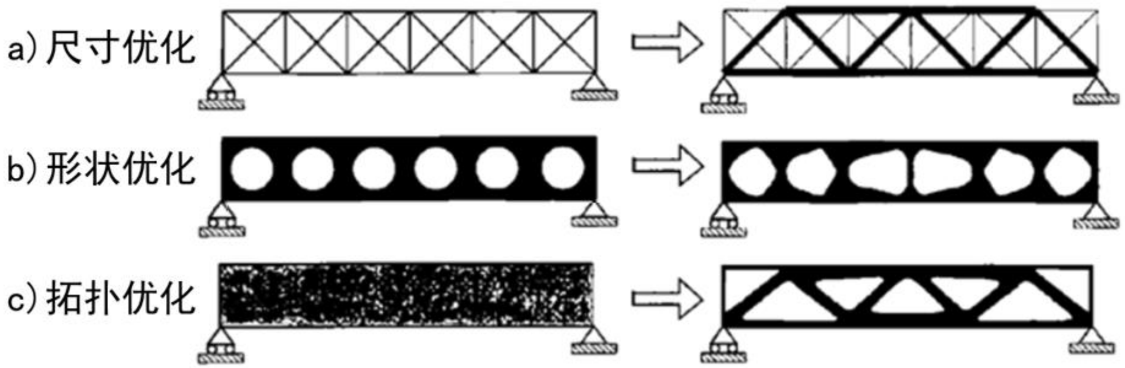


Fig. 9 Comparative illustration of the different optimization strategies[7]

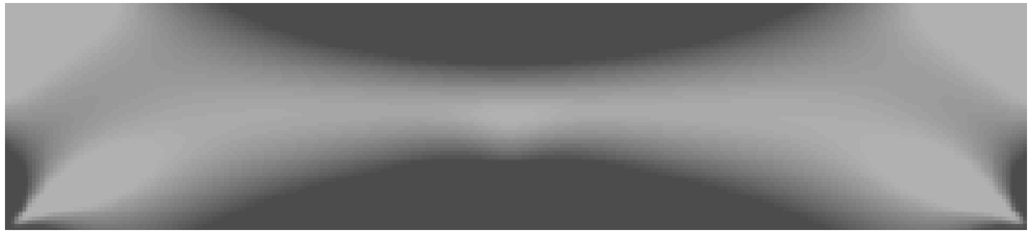


Fig. 10 Compliance minimization of the MBB problem[8]

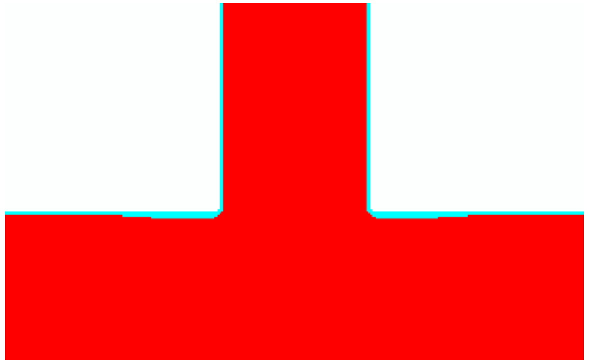


Fig. 11 Stress-constrained multi-material topology optimization[9]

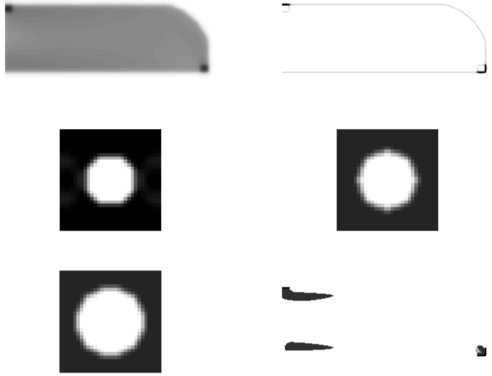


Fig. 12 Multi-scale topology optimization

Fig. 13 Lattice topology optimization

Fig. 14 Topology optimization of the aero-bracket[10]

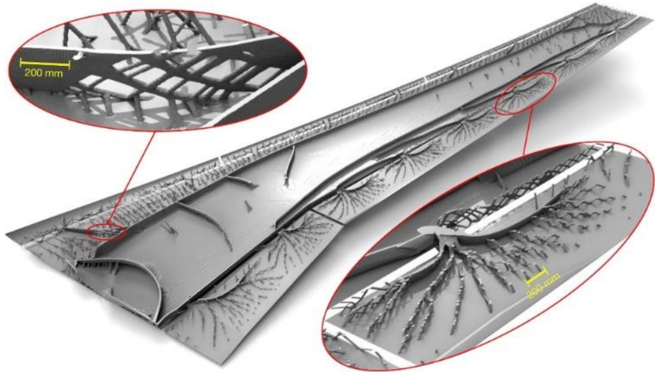


Fig. 15 Wing structure topology optimization[11]

Fig. 16 Building structure topology optimization[12]

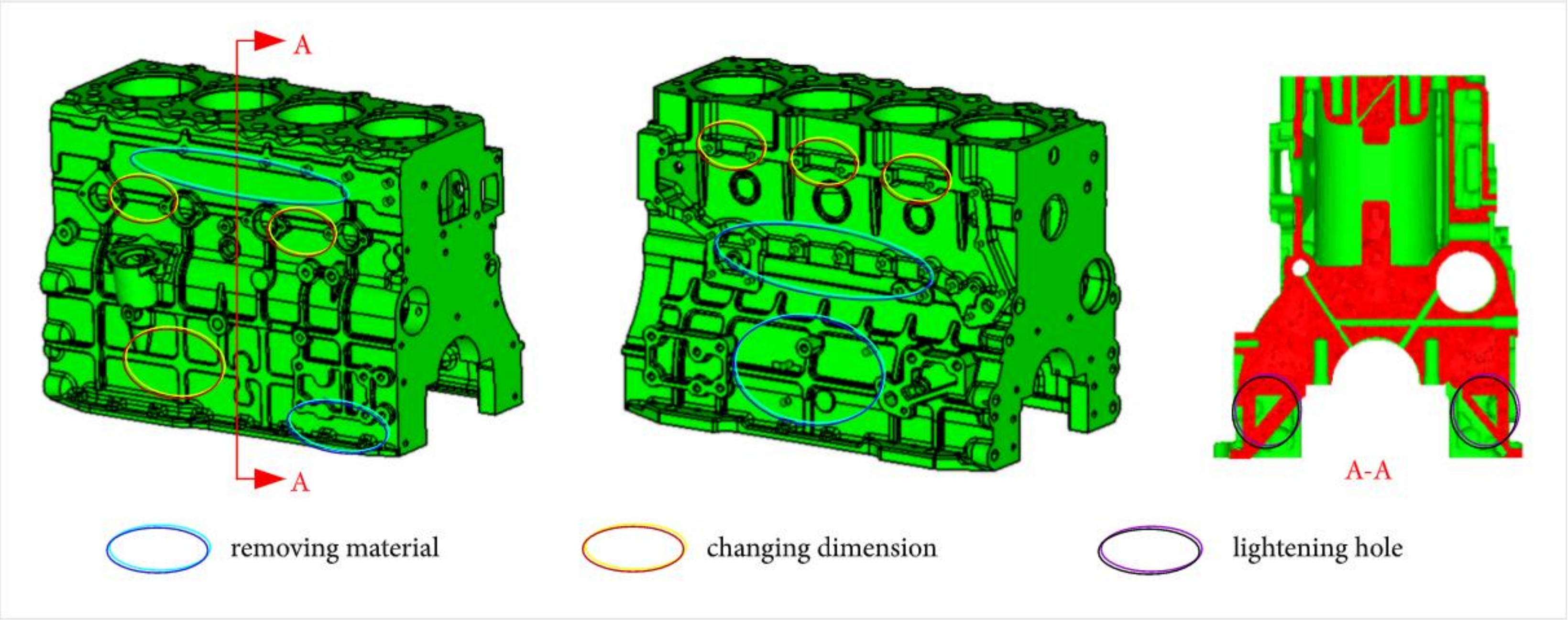


Fig. 17 Topology optimization of the engine block[13]

Fig. 18 Topologically optimized piston rod[14]

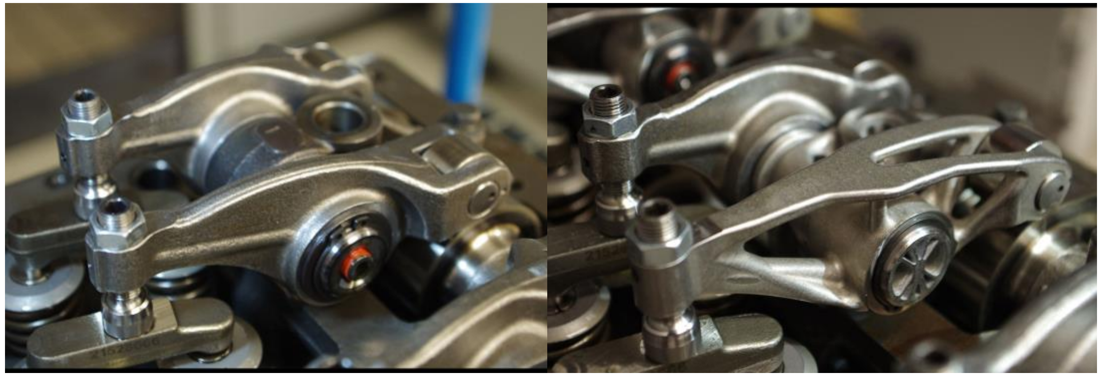


Fig. 19 Topologically optimized Euro 6 DTI5 rocker arm for Renault Trucks[15]

Fig. 20 Additive manufactured pistons run in Porsche GT2 RS (20% weight reduction)[16]

Fig. 21 Titanium additive manufactured automotive piston (23.5% weight reduction) [17]

Challenges in Topology Optimization: Manufacturability Issue

Casting

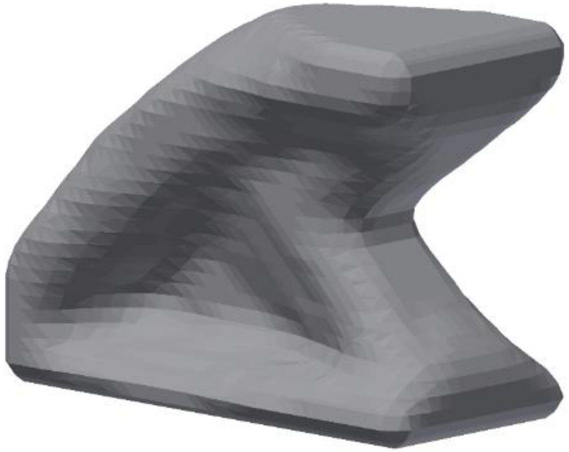
- Unmanufacturable undercuts and interior voids
- Directional material removal

CNC machining

- Cutting tool accessibility
- Multi-directional multi-layer density filtering
- Accessibility constraint for level set method

Stamping metal forming

- Large-scale computing for thin walled structures
- Shape/Topography optimization
- Mesh-free topology optimization



ALTO (Accelerated super-Lightweight TopOpt)

- Motivation:

Existing topology optimization methods are inefficient and even ineffective in super lightweight structure design since both computational cost and minimum member size are strongly dependent on scale of the background mesh.

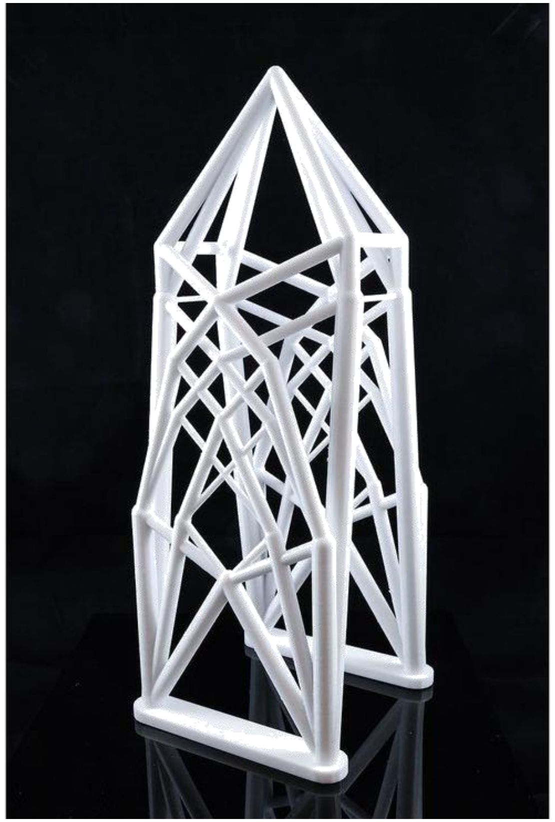
- Basic idea

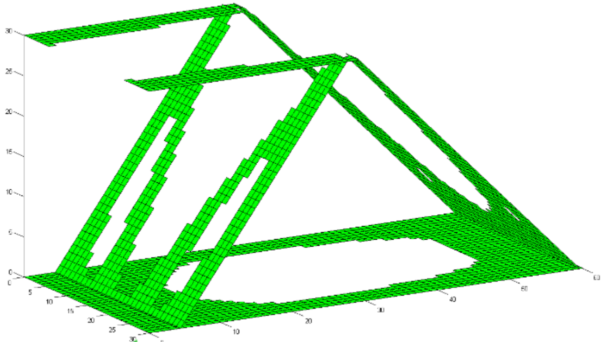
Starting from a set of arbitrarily placed shells within the design domain, perform concurrent optimization on the shell layout and in-shell material distribution.

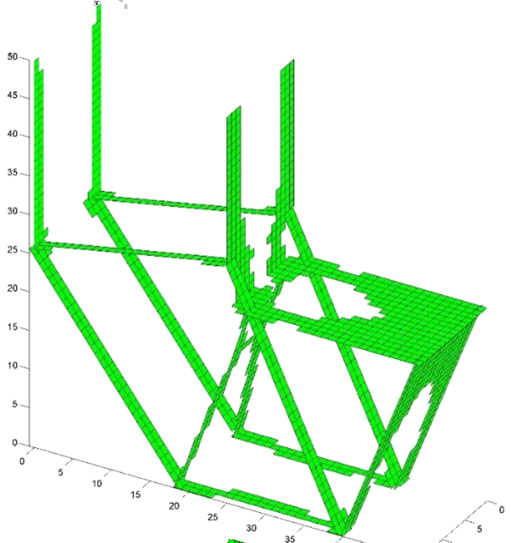
- Characteristics:

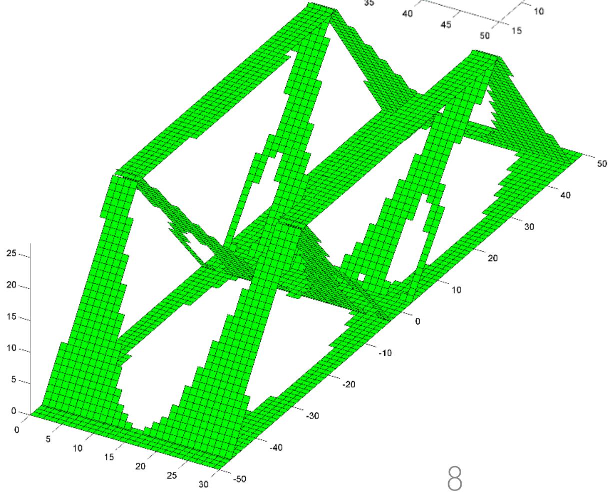
(1) Eliminates the 3D background mesh by a set of shell elements and thus the numerical optimization is significantly accelerated, especially compared to the recently popular moving plate approaches.

(2) The target material volume fraction can be extremely small, like below 1%, and very importantly, the mesh size is non-sensitive to the target material volume fraction.









Challenges in Topology Optimization: Software Aspect

Shortage in optimization problem setup

Poor support to multi-objective topology optimization problem with hybrid constraints

Limited support to manufacturing constraints

A limited number of manufacturing constraint options, e.g., unidirectional casting constraint

Non-trivial pre and post-processing effort

Model simplification (poor support to large scale computing); Regeneration of frozen CAD models

Brief Introduction to Additive Manufacturing

kmwe.com

- Join materials to make objects from 3D CAD models
- Main techniques
  - Direct energy deposition: *LENS*
  - Powder bed fusion: *EBM, DMLS*
  - Binder jetting: *ExOne*
  - Photopolymerization: *SLA*
  - Material extrusion: *FDM*
  - Material jetting: *Connex Polyjet*
- Applications
  - Prototype and part manufacture
  - Biomedical usage
  - Part repairing

Fig. 22 Urbee Hybrid：the world’s first 3D printed car [18]

Fig. 23 LightCocoon’s cover is flexible and can weight as little as 19 grams per square meter [19]

Fig. 24 In 2014, the world’s first 3D-printed electric car :“Strati”[20]

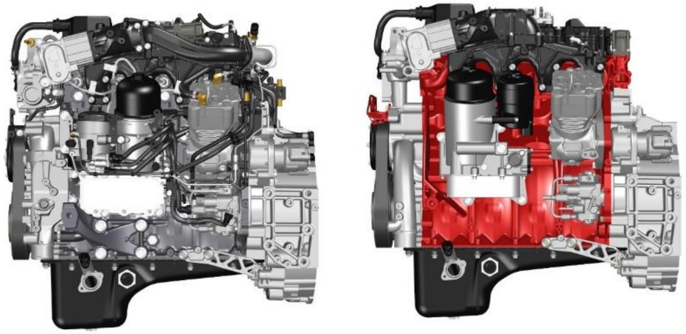
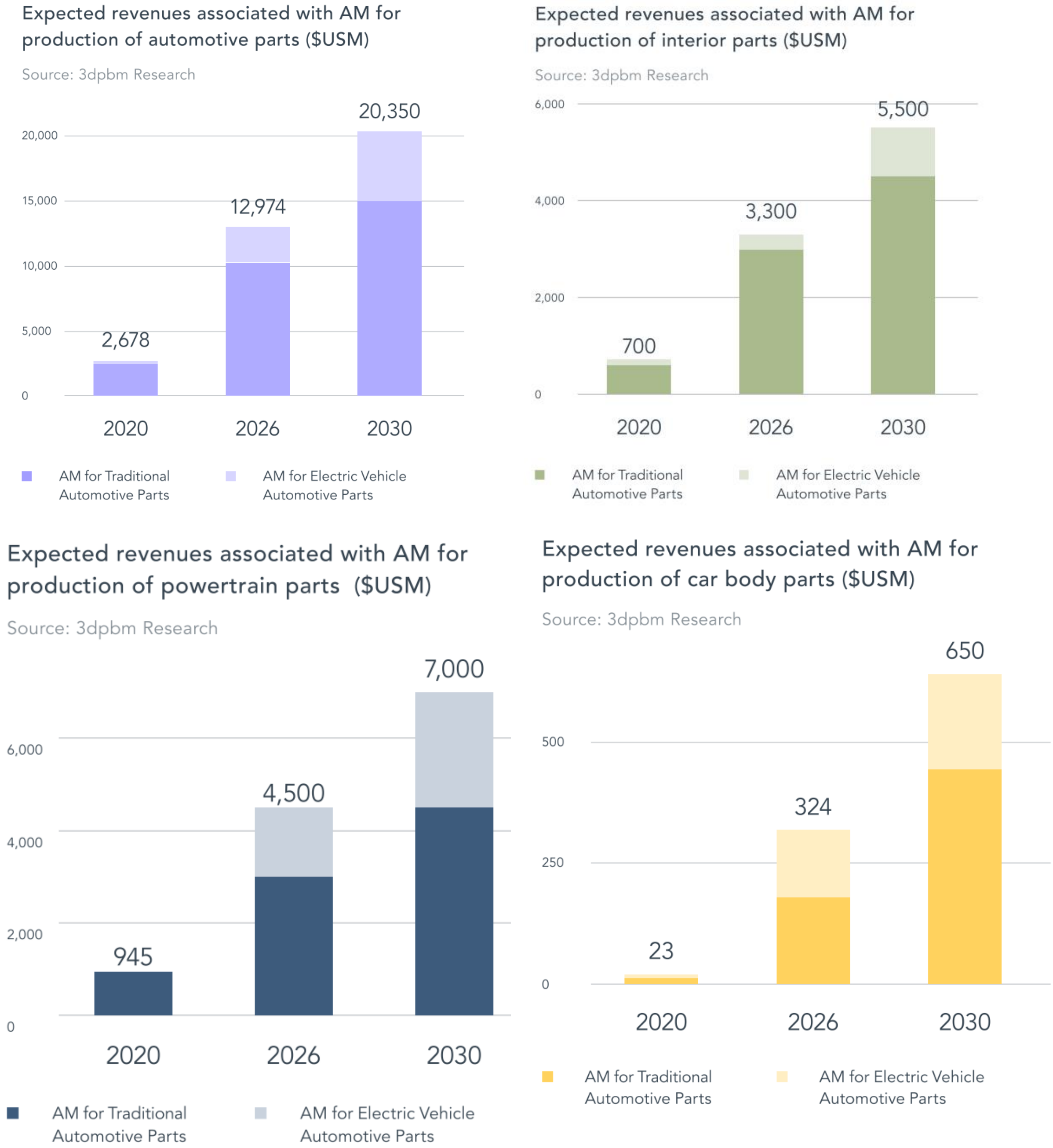


Fig. 25 Renault Trucks DTI5 Euro 6 engine, 841 parts; Right: Same engine, designed with 3D metal printing 4-Cylinder Engine by using 25% less components[21]



Expected revenues associated with AM for production of automotive parts ($USM)

Source: 3dpbm Research

Expected revenues associated with AM for production of interior parts ($USM)

Source: 3dpbm Research

Expected revenues associated with AM for production of powertrain parts ($USM)

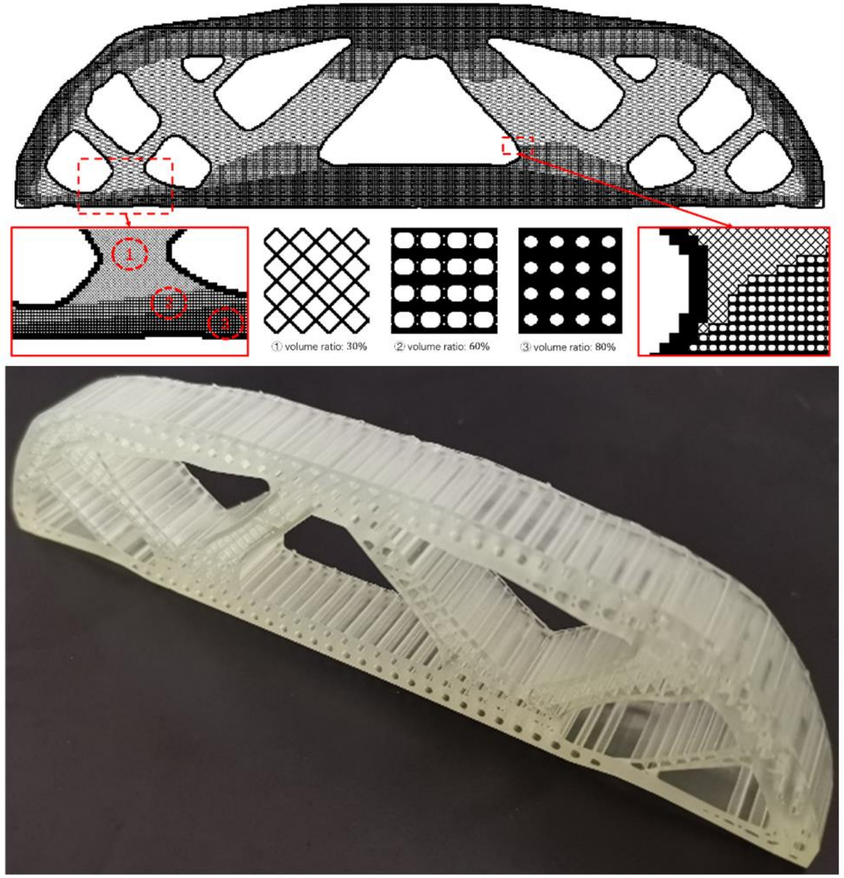
Source: 3dpbm Research

Expected revenues associated with AM for production of car body parts ($USM)

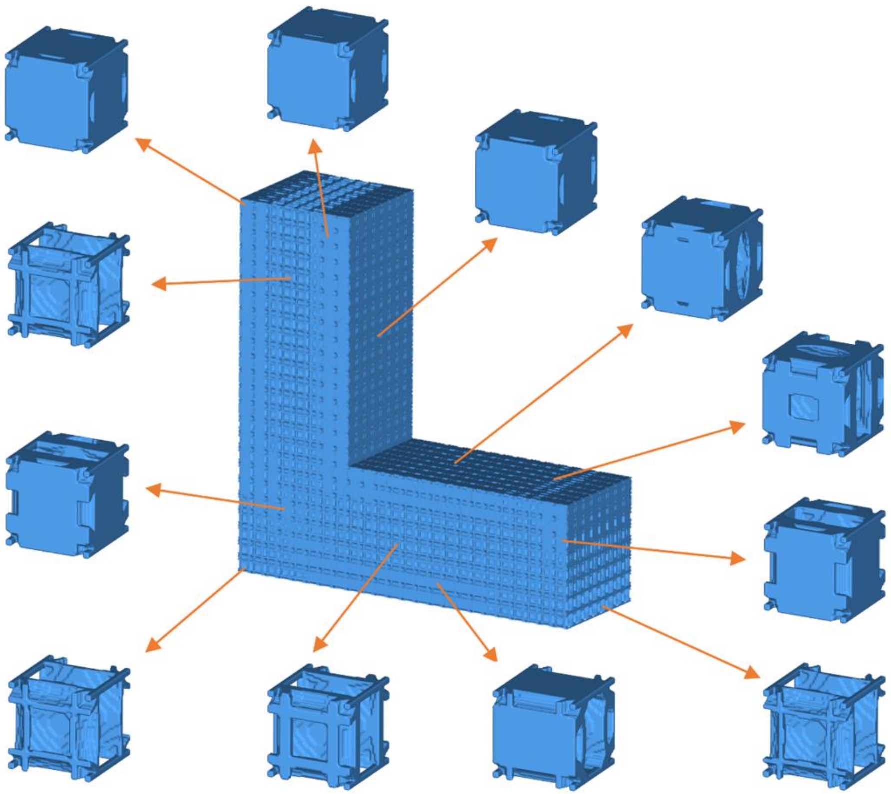
Source: 3dpbm Research

Fig. 26 The expected revenues of automotive parts associated with AM[22]

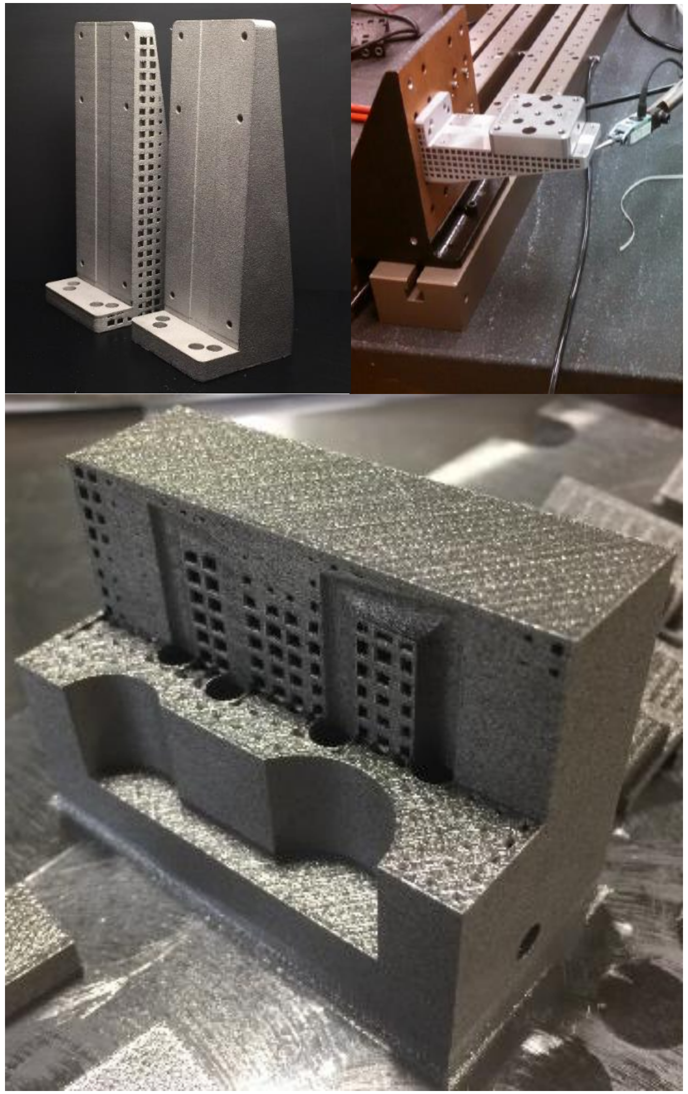
Multiscale TopOpt



Multiscale TopOpt for DLP 3D printing



Lattice structure TopOpt



SLM manufacturing of the lattice structures

Support Structure

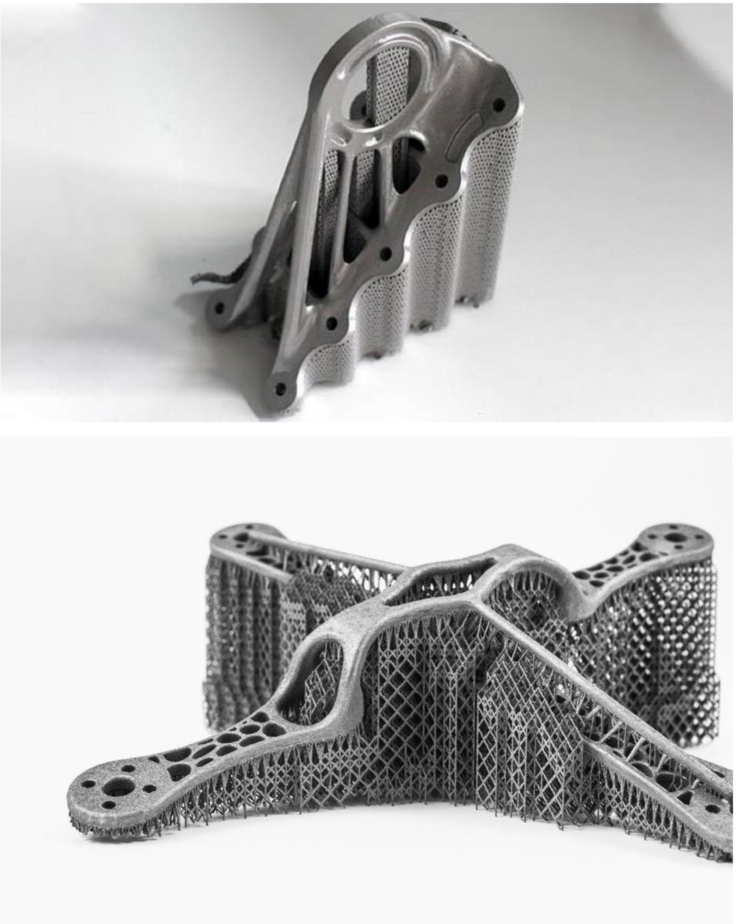
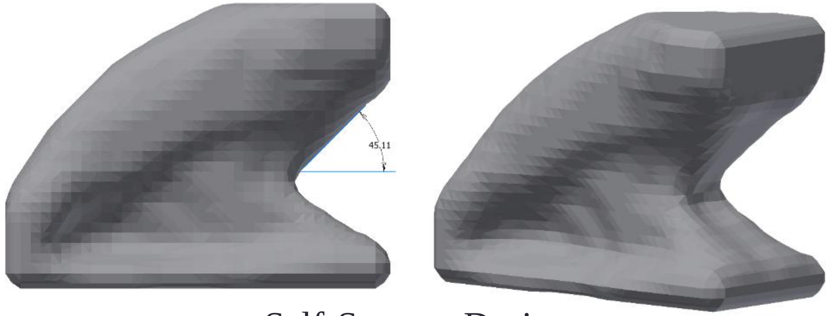
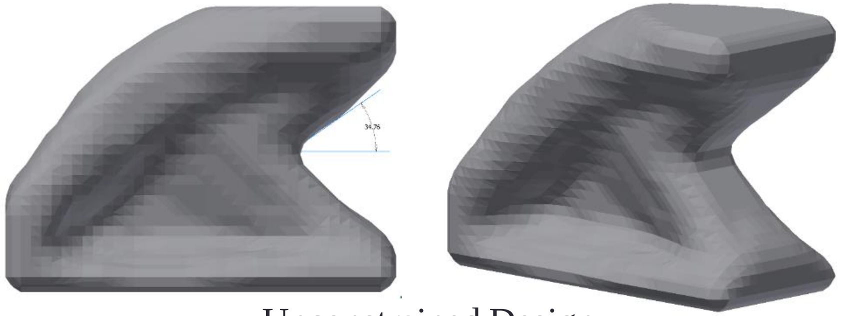


Fig. 27 Sacrificial supports in metal additive manufacturing[23,24]

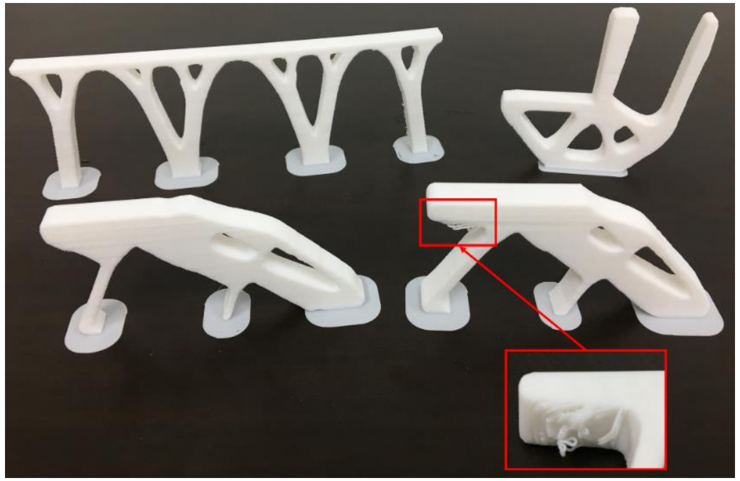
Self-Support Threshold Condition Test



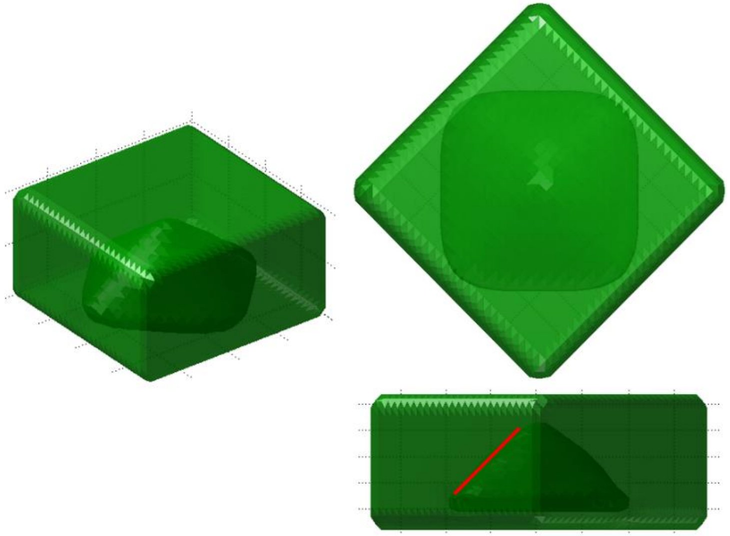
Self-Support Design



Unconstrained Design

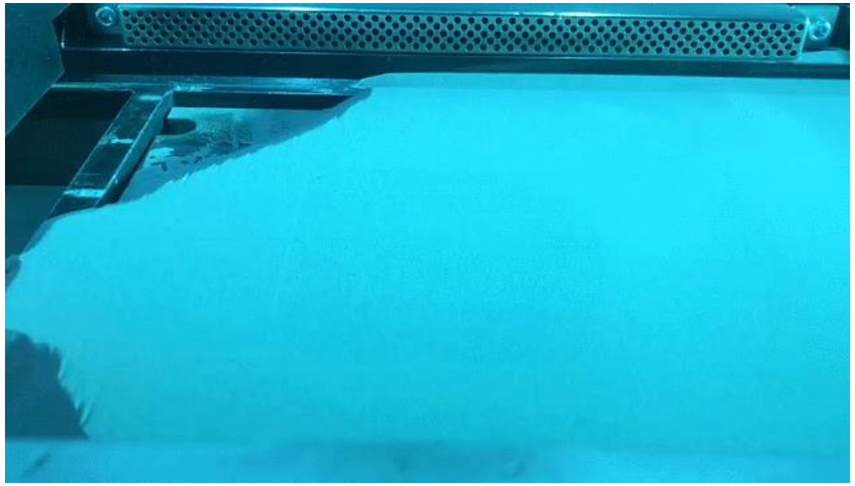


Self-Support Topology Optimization

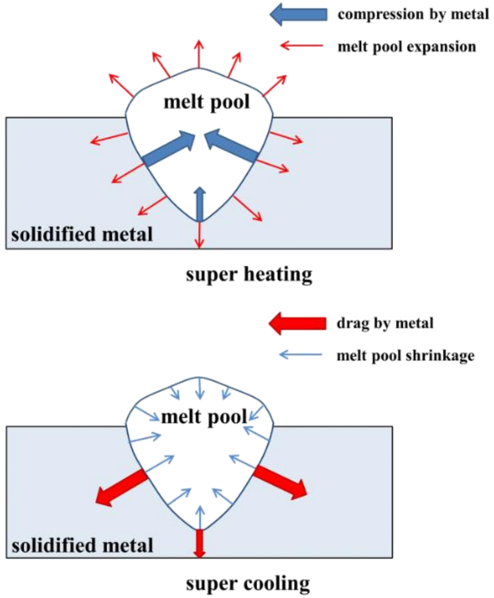


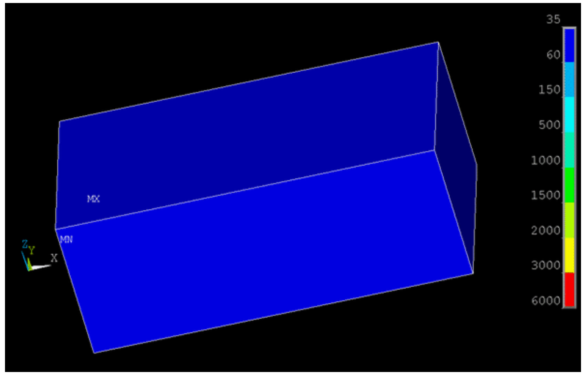
Self-Support Interior Design

Residual Stress and Distortion



DMLS printing process





two-layer detailed simulation

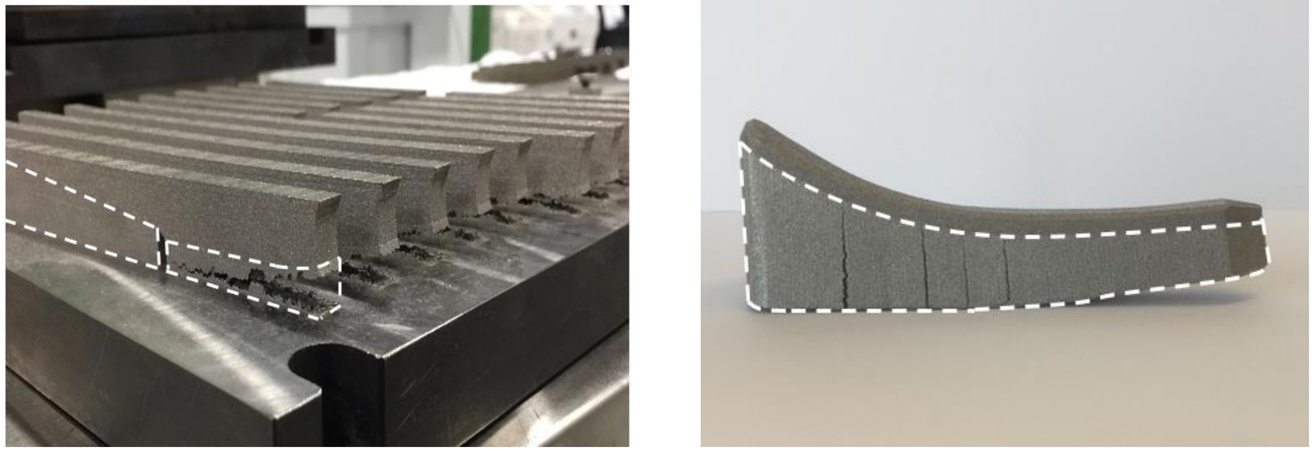


Fig. 28 Crack defect of metallic additive manufacturing parts

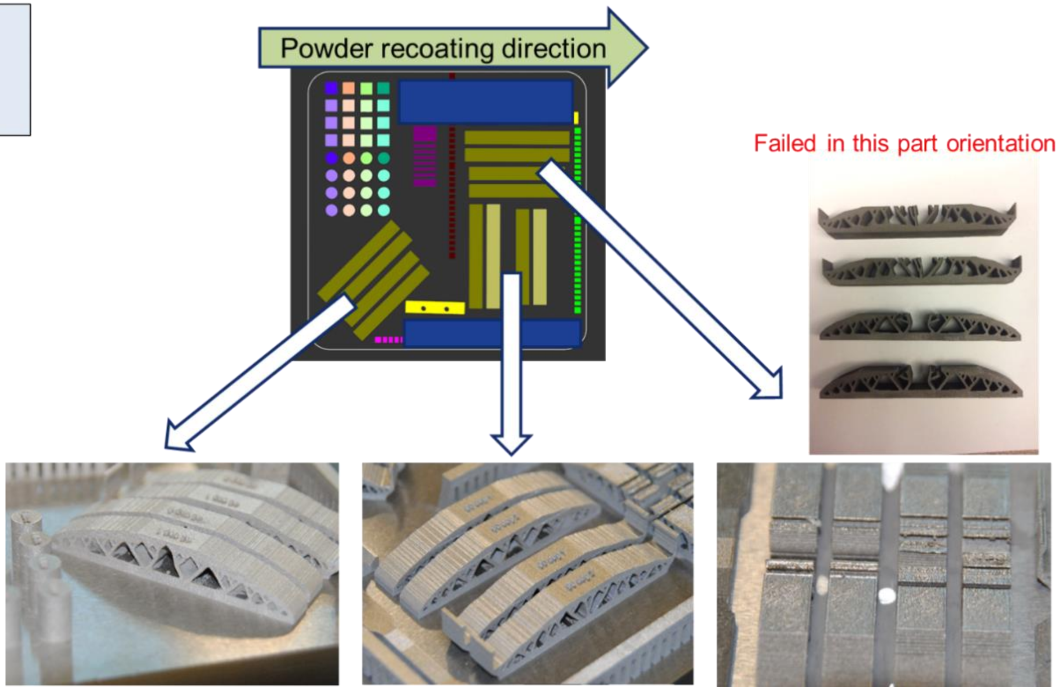
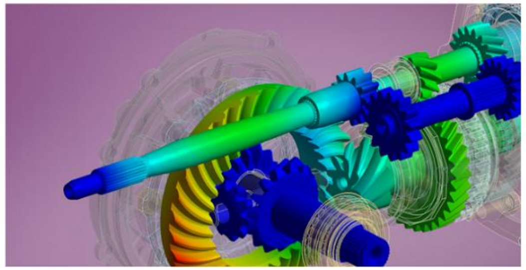
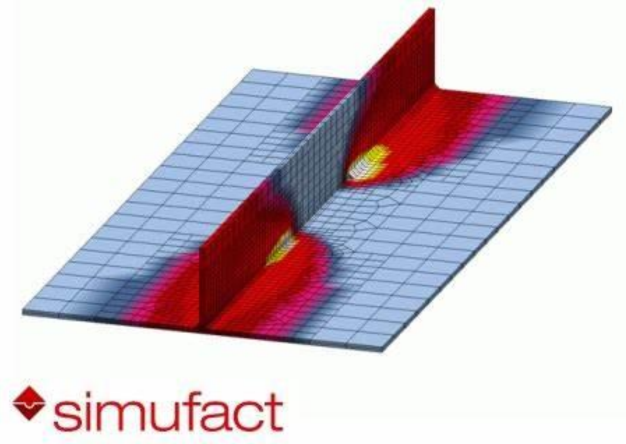


Fig. 29 Distortion defect of metallic additive manufacturing parts

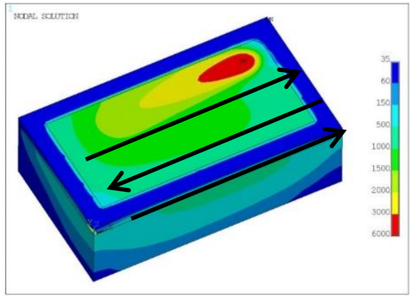
Fast Prediction of Residual Stress and Distortion



ANSYS 3DSIM

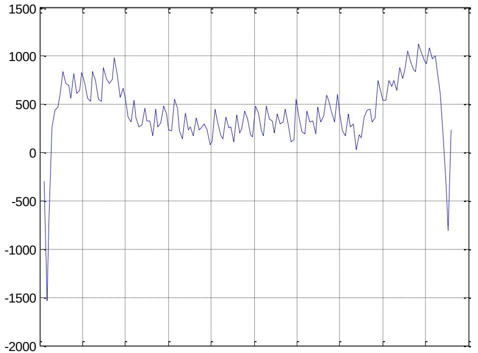


MSC Simufact



RVE process model

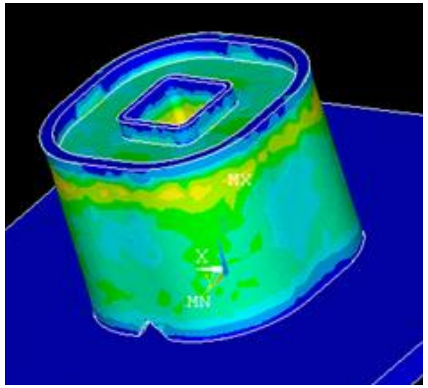
Detailed process simulation



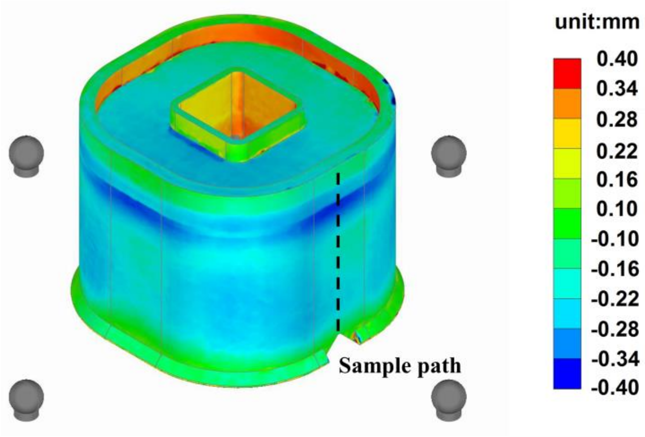
Obtain inherent strain model

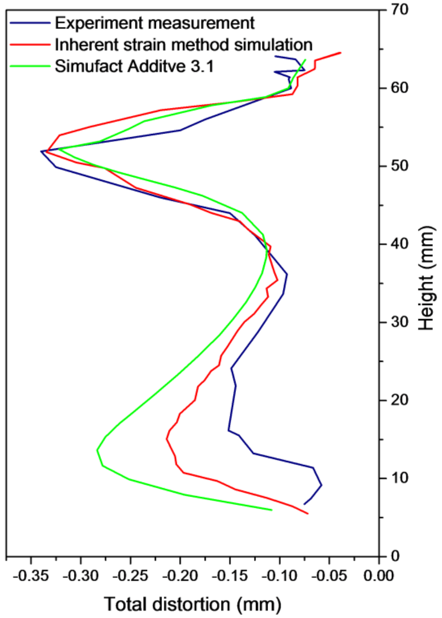
Assign inherent strains

Static mechanical analysis



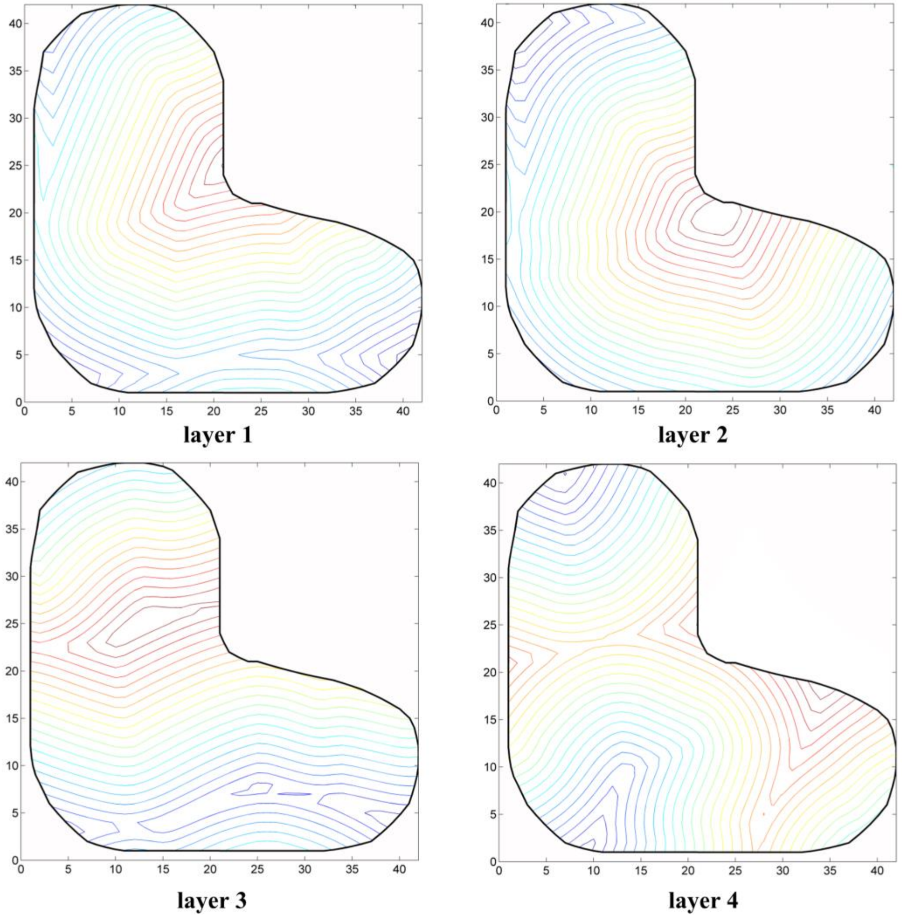
Residual distortion





Optimal Control of Residual Stress and Distortion

Fig. 30 Residual stress-constrained TopOpt[25]



layer 1

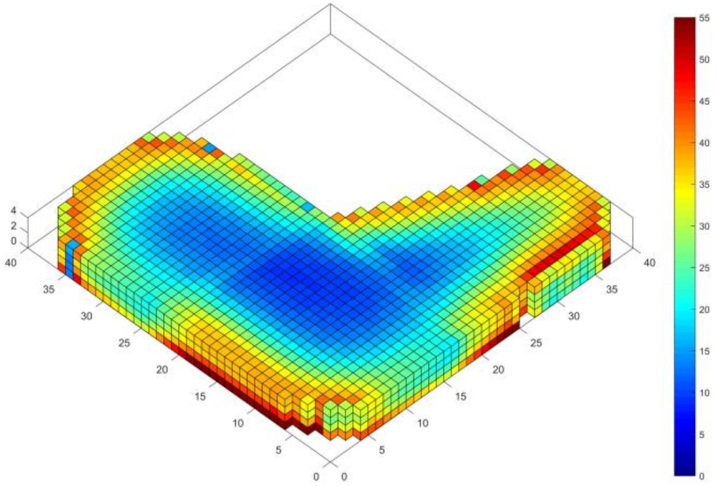
layer 2

layer 3

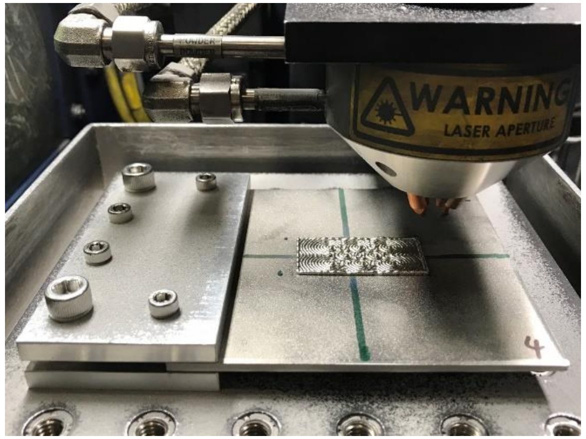
layer 4

Fig. 31 Laser scanning path optimization

Maximum residual stress reduced by 26%!



Residual stress distribution

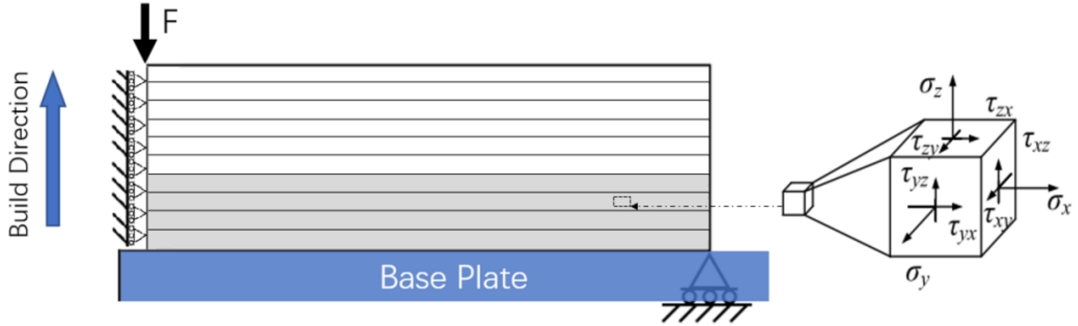


Validating experiment setup

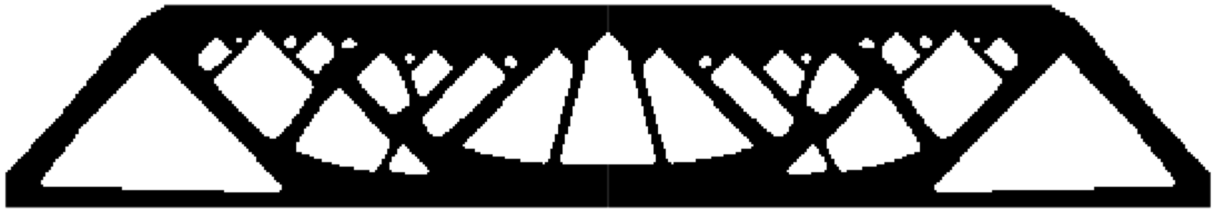
MBB example

The material adopted in this work is Ti6Al4V, which has Young's modulus of 110 GPa, Poisson's ratio of 0.3, and yield strength of 1160 MPa. In this work, the inherent strain value is set as $\epsilon_x^{ihs} = \epsilon_y^{ihs} = -0.002$.

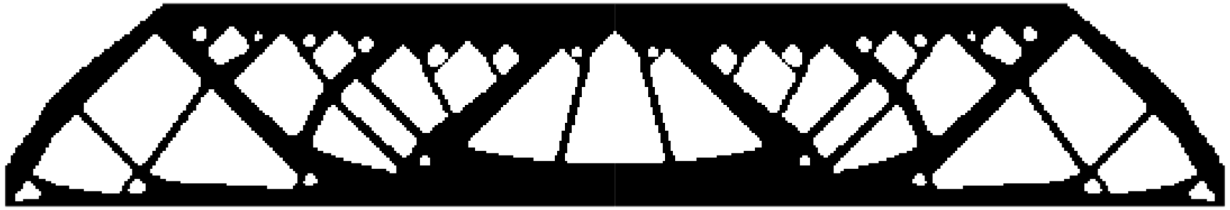
L = 240mm and H = 40mm



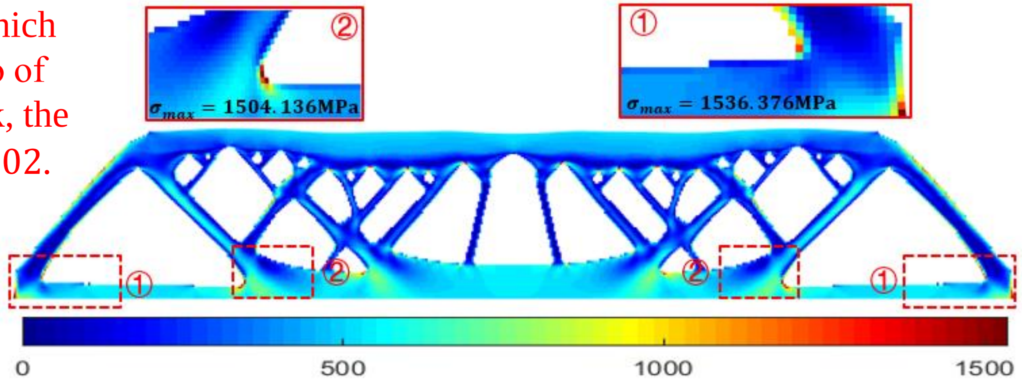
Boundary condition for the MBB beam

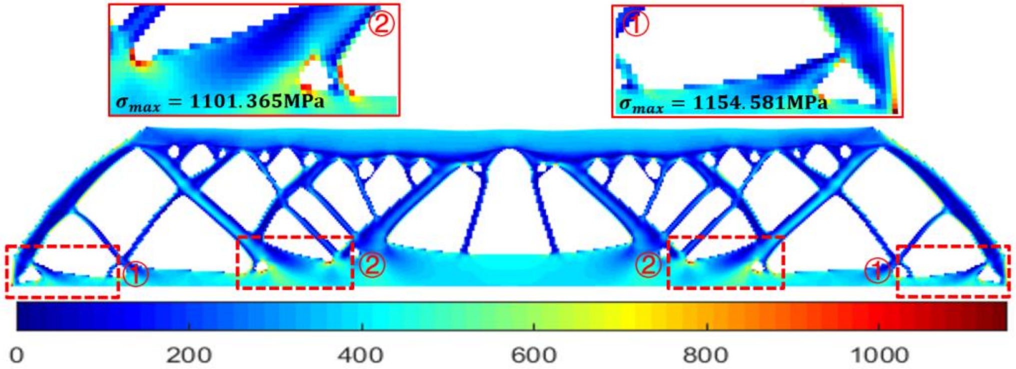


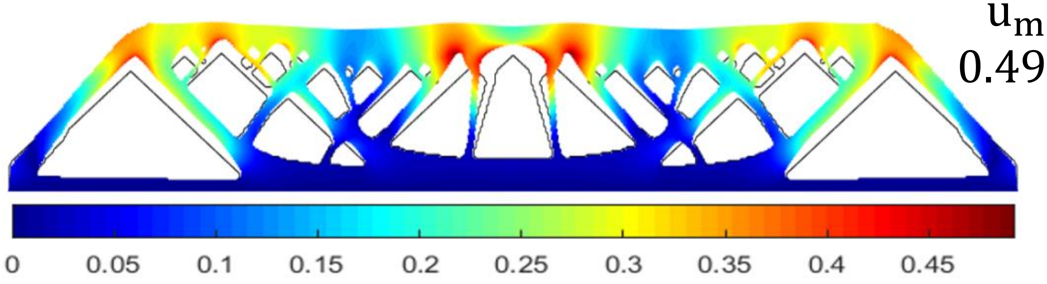
with self-support but without residual stress constraint



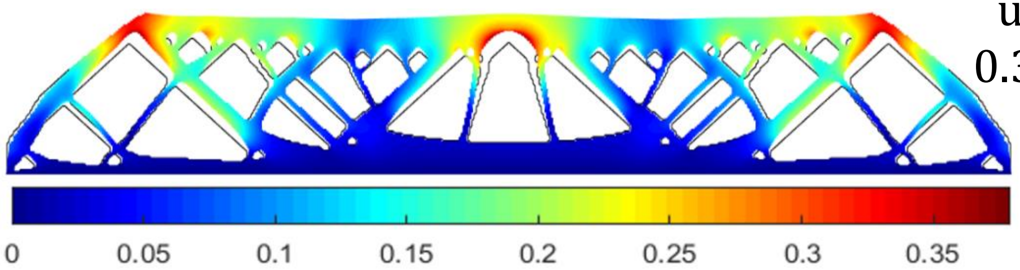
with self-support and with residual stress constraint







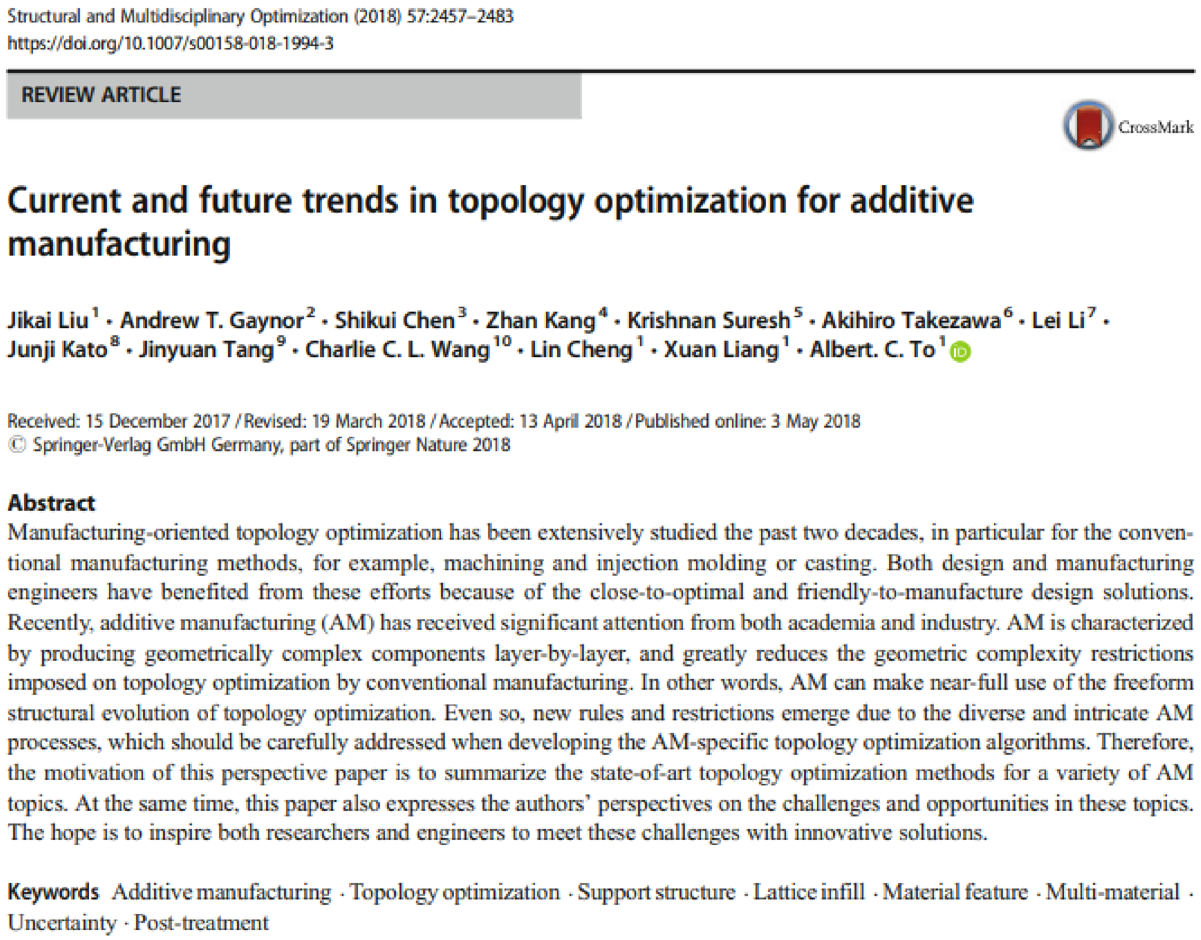
u_{max} = 0.496 mm



u_{max} = 0.375mm

Research Vision

- More challenges to address than already solved issues.



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REVIEW ARTICLE

Current and future trends in topology optimization for additive manufacturing

Jikai Liu[1] · Andrew T. Gaynor[2] · Shikui Chen[3] · Zhan Kang[4] · Krishnan Suresh[5] · Akihiro Takezawa[6] · Lei Li[7] · Junji Kato[8] · Jinyuan Tang[9] · Charlie C. L. Wang[10] · Lin Cheng[1] · Xuan Liang[1] · Albert. C. To[1]

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Abstract

Manufacturing-oriented topology optimization has been extensively studied the past two decades, in particular for the conventional manufacturing methods, for example, machining and injection molding or casting. Both design and manufacturing engineers have benefited from these efforts because of the close-to-optimal and friendly-to-manufacture design solutions. Recently, additive manufacturing (AM) has received significant attention from both academia and industry. AM is characterized by producing geometrically complex components layer-by-layer, and greatly reduces the geometric complexity restrictions imposed on topology optimization by conventional manufacturing. In other words, AM can make near-full use of the freeform structural evolution of topology optimization. Even so, new rules and restrictions emerge due to the diverse and intricate AM processes, which should be carefully addressed when developing the AM-specific topology optimization algorithms. Therefore, the motivation of this perspective paper is to summarize the state-of-art topology optimization methods for a variety of AM topics. At the same time, this paper also expresses the authors' perspectives on the challenges and opportunities in these topics. The hope is to inspire both researchers and engineers to meet these challenges with innovative solutions.

Keywords Additive manufacturing · Topology optimization · Support structure · Lattice infill · Material feature · Multi-material · Uncertainty · Post-treatment

Hybrid Additive-Subtractive Manufacturing

- Hybrid additive-subtractive manufacturing (HASM) indicates the combination of additive manufacturing (AM) and subtractive manufacturing (SM) techniques to form a new manufacturing strategy that makes up the individual’s shortcomings.

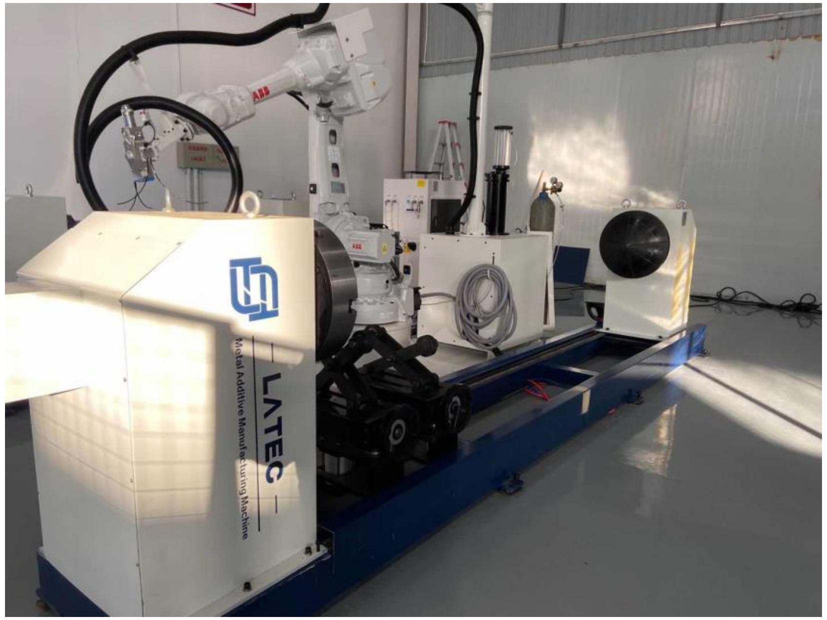
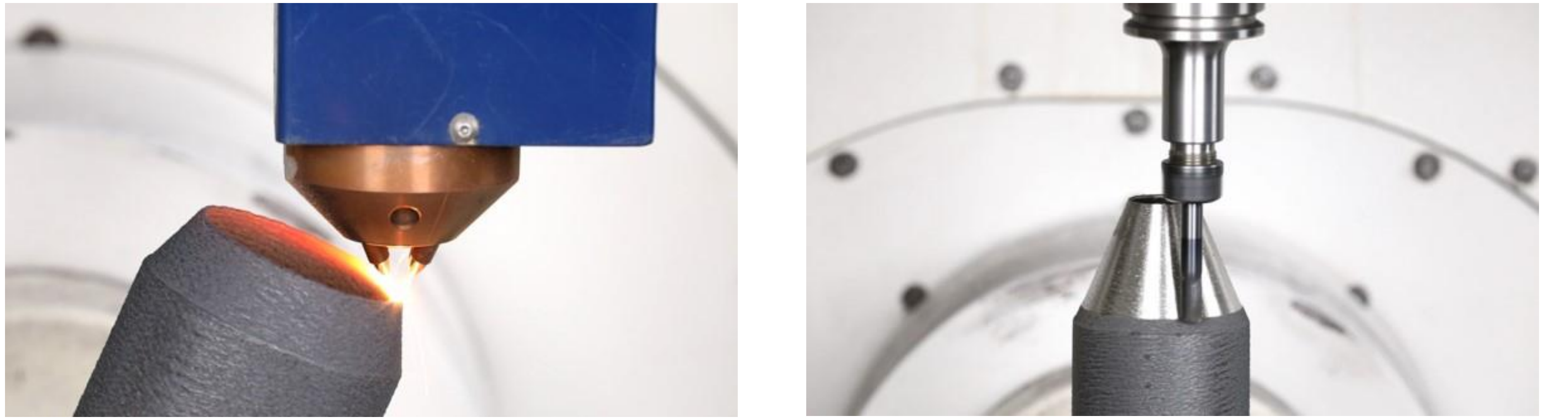


Fig. 33 LATEC LOM-3000

Fig. 32 DMG LASERTECH 65 3D Hybrid



Process planning for Hybrid Additive-Subtractive Manufacturing

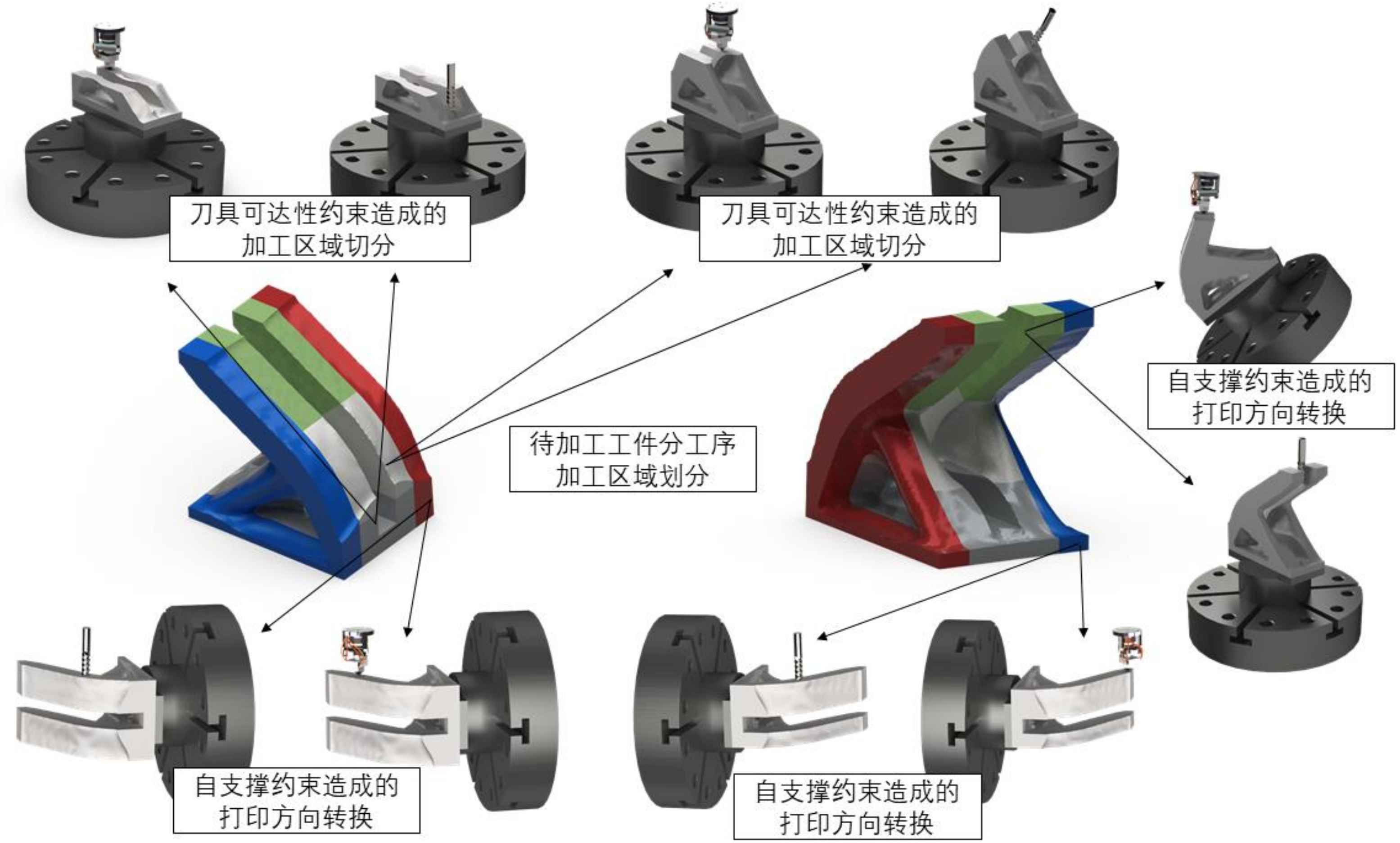
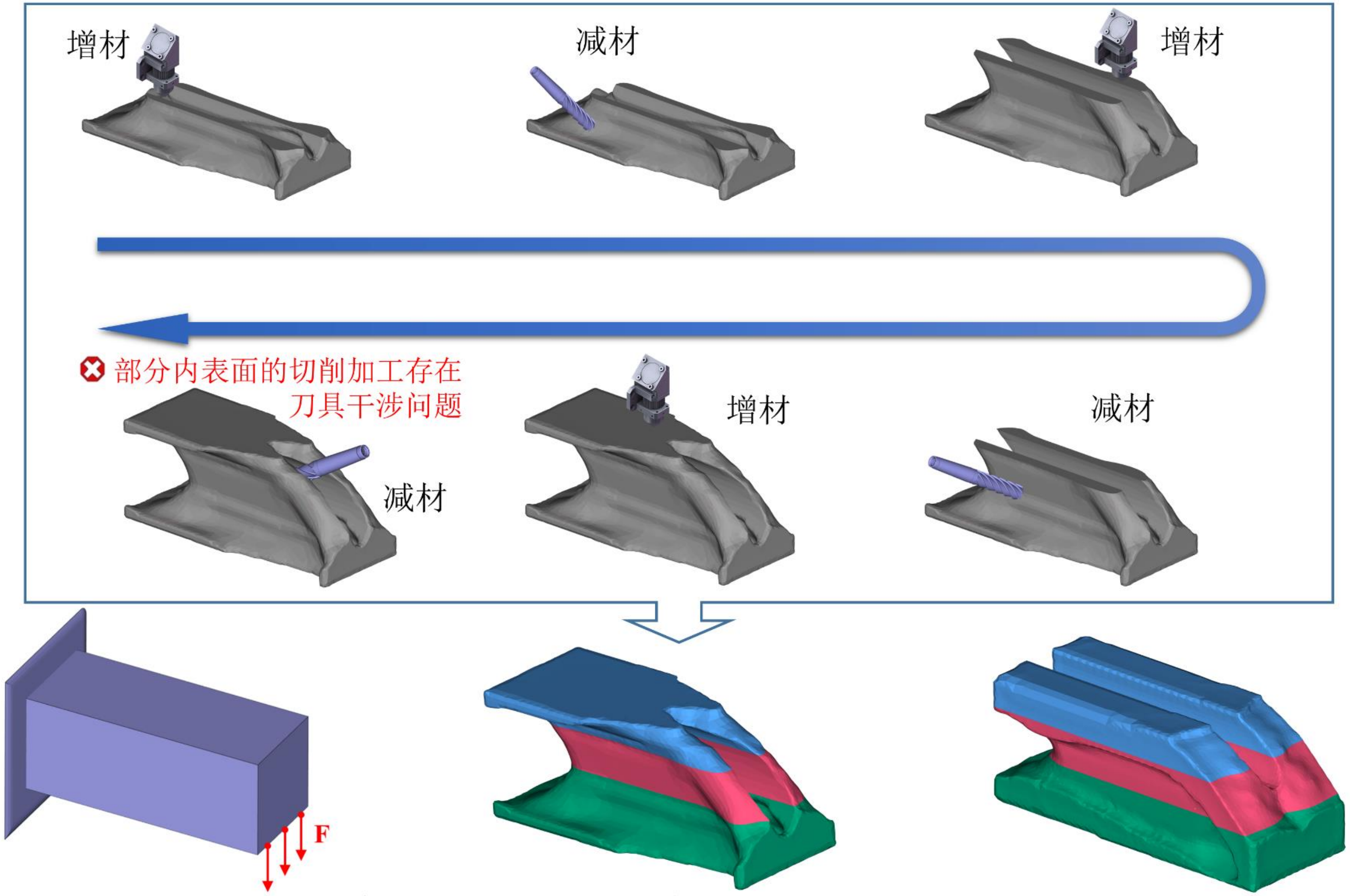


Fig. 34 Hybrid AM-SM process plan of a topologically optimized part

Fig. 35 A turbine case manufactured through LASERTEC 65 3D hybrid[26]

TopOpt for Hybrid Additive-Subtractive Manufacturing



(a)拓扑优化设计域及边界条件

(b)传统拓扑优化设计
及其增减材制造方案

(c)增减材可制造性约束下的
拓扑优化设计

Fig. 36 Topology optimization for hybrid additive-subtractive manufacturing

Conclusion and Future Perspectives

Lightweight Design

- ☐ Large-scale TopOpt
- ☐ Multidisciplinary TopOpt
- ☐ TopOpt for Manufacturing
- ☐ TopOpt Software Tools

Advanced Manufacturing

- ☐ Additive Manufacturing
- ☐ Simulation for AM
- ☐ Process Optimization
- ☐ Hybrid Manufacturing
- ☐ Process planning for HM

Thank you！

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