Semnan University
Additive Manufacturing Laboratory (AML)

آزمایشگاه تحقیقاتی
ساخت افزایشی
دانشگاه سمنان

مباحث منتخب (ساخت افزایشی)

طراحی و مواد

استاد درس:

دکتر عبدالواحد کمی

نیمسال اول ۱۴۰۰

قابلیت‌های AM در طراحی

- **انواع پیچیدگی‌های قابل دستیابی با AM:**

✓ شکلی

✓ سلسله مراتبی

✓ کاربردی

✓ مواد

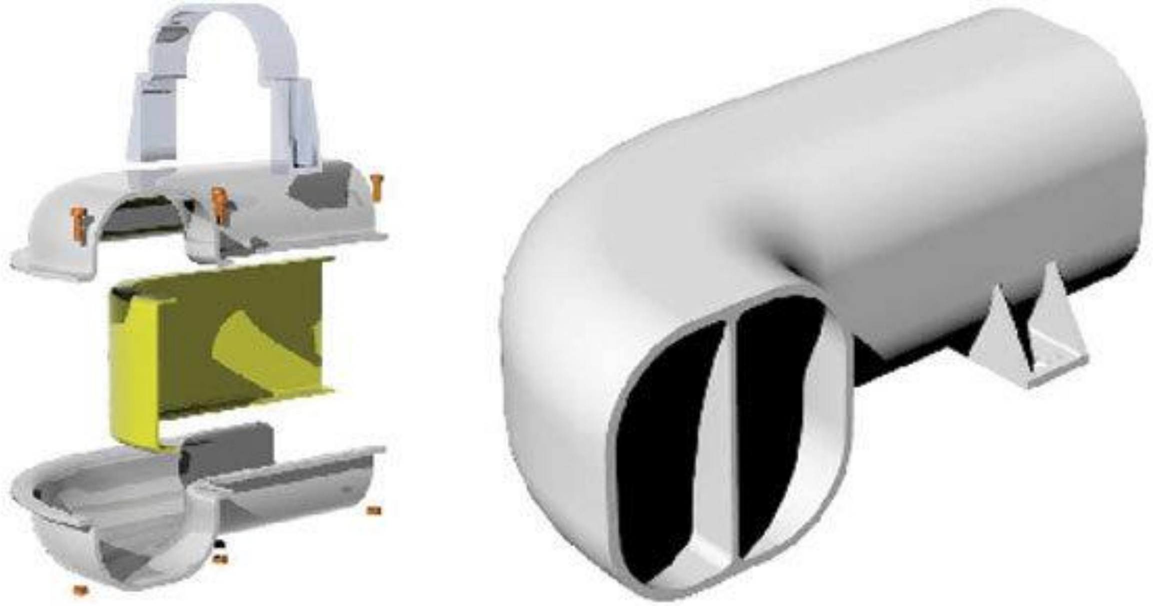
✓ هندسه

✓ بازطراحی

✓ طراحی ویژه تجاری

Value Drivers

- Easier to design
- Less supply chain
- No tooling
- Less Labor
- No assembly error
- Less certification
- Lighter Product
- Better!

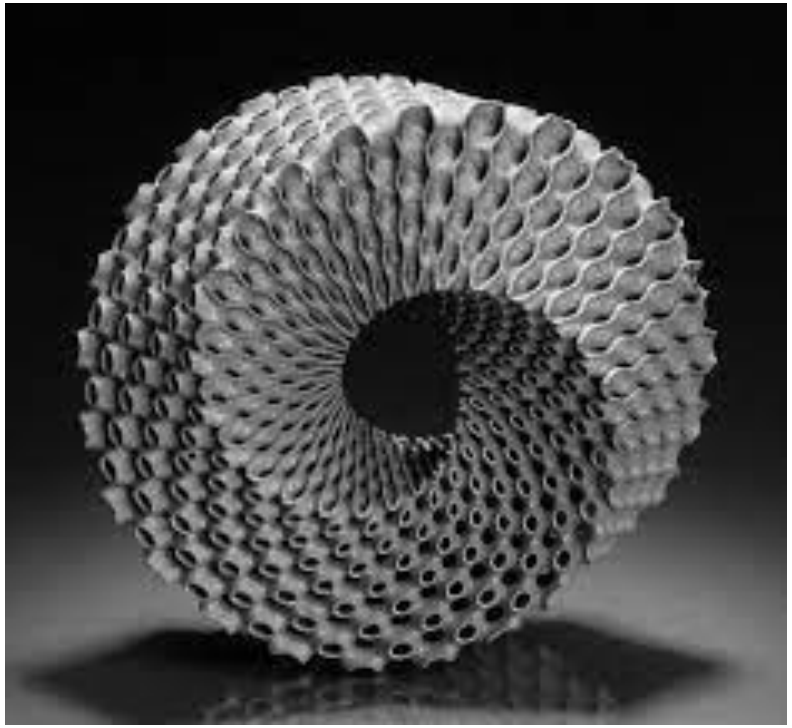


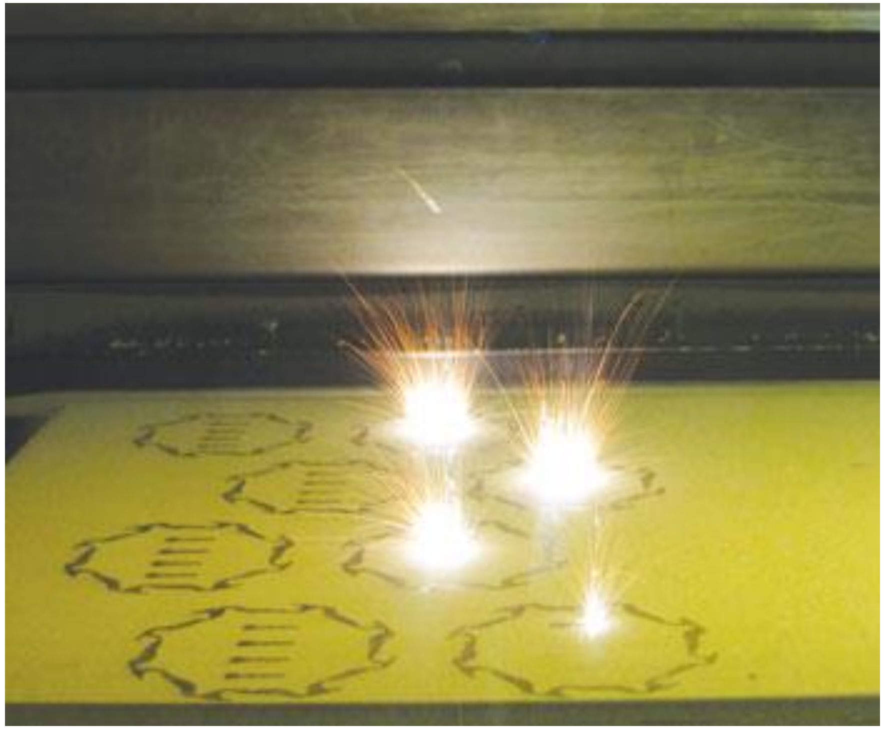
Duct: conventional
Assembled, vacuum form
Part Count = 16 plus glue

Duct: consolidated for additive
Fabrication with SLS
Part Count = 1

قابلیت‌های AM در طراحی: پیچیدگی شکلی

- پیچیدگی شکلی هر لایه تأثیری در ساخت لایه ندارد.
- مقایسه با فرایندهای سنتی مانند ماشینکاری و تزریق پلاستیک





قابلیت‌های AM در طراحی: پیچیدگی سلسله مراتبی

- در مقیاس میکرو (**ریزساختار**): توانایی ایجاد رفتار (مکانیکی، سایشی، خوردگی و ...) متفاوت در بخش‌های مختلف قطعه

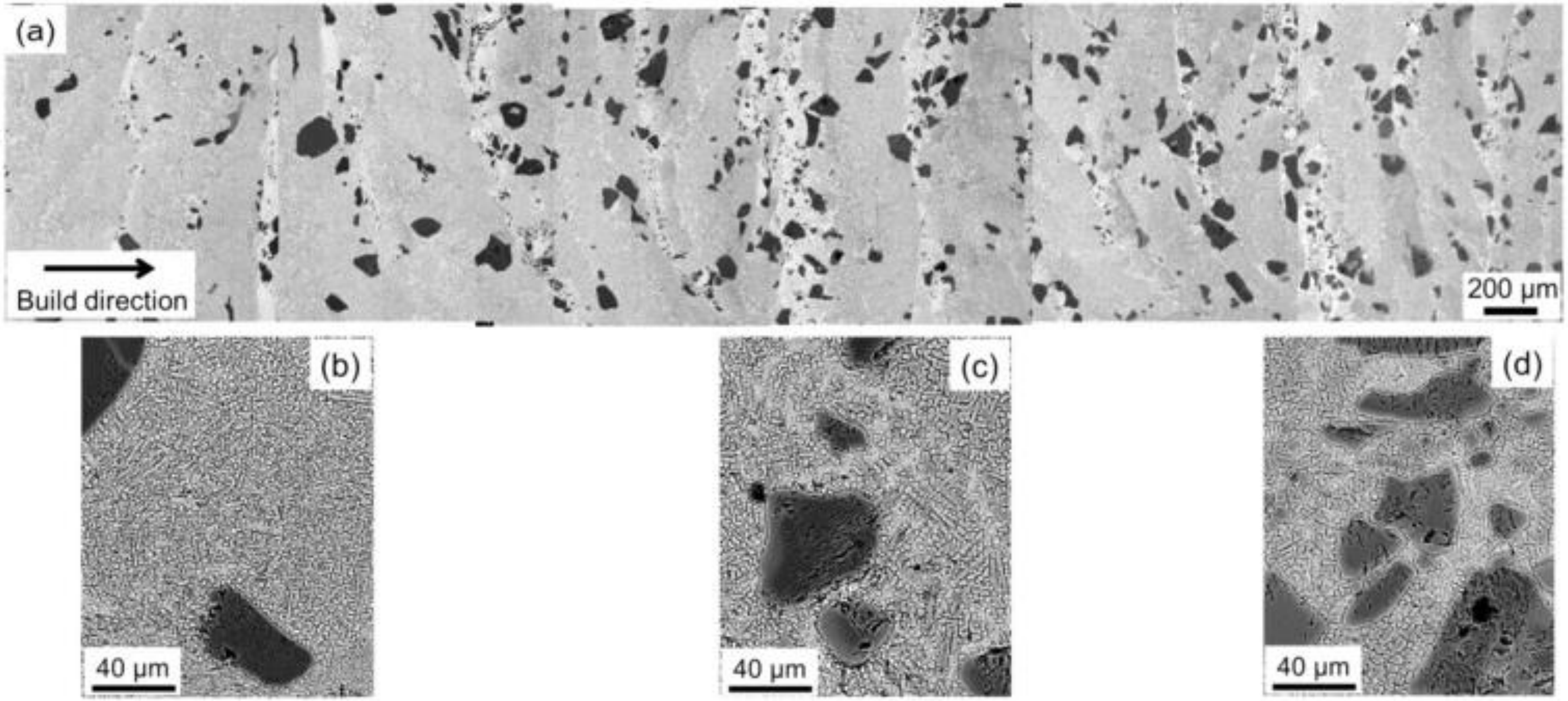
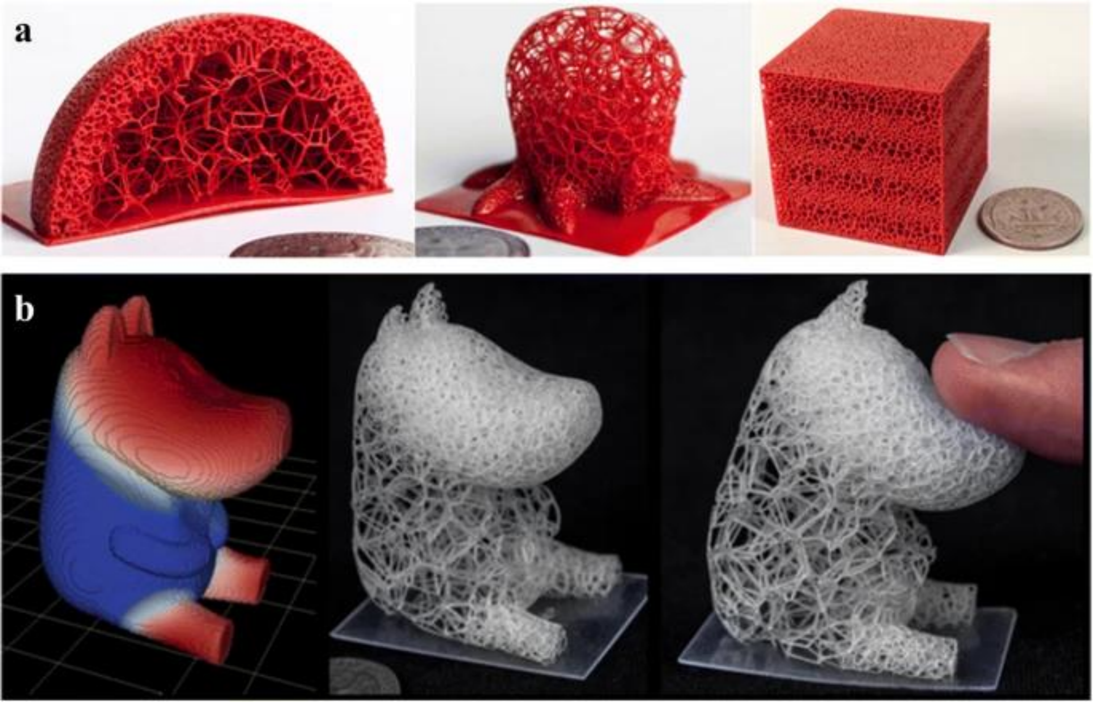


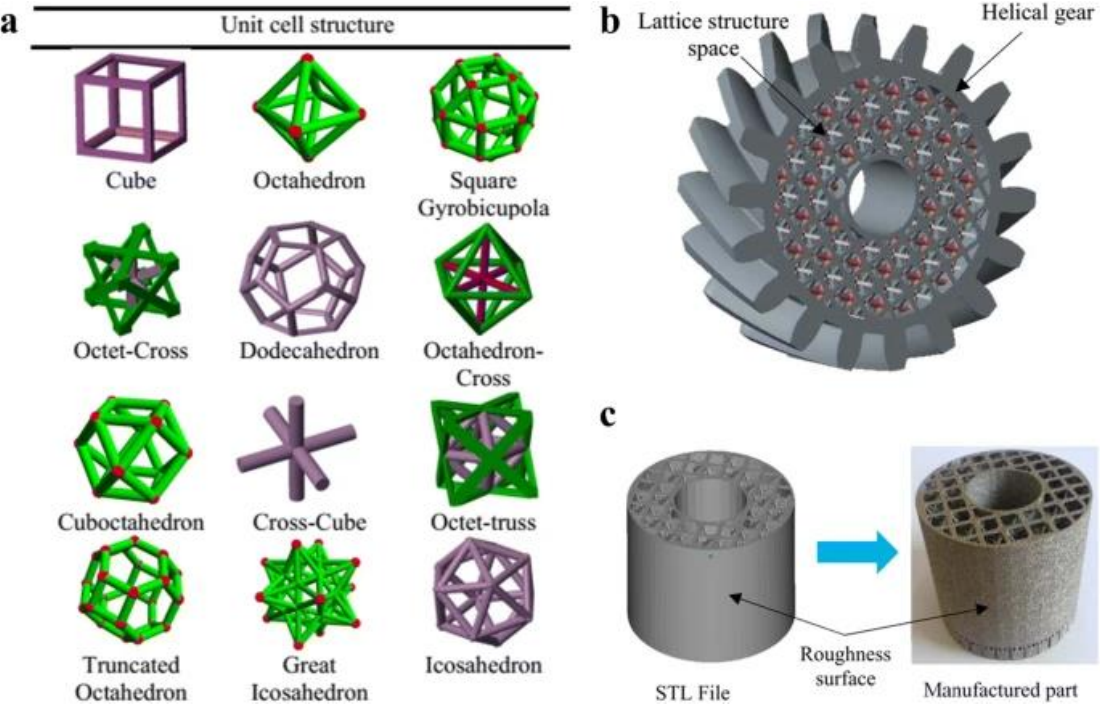
Fig. 9. (a) Stack of back-scattered electron images covering the entire cross-section of the gradient Ti/TiC composite. (b-d) Magnified images highlighting the changes in the fractions of undissolved TiC particles, taken from locations where the expected TiC content is 20%, 40% and 60%.

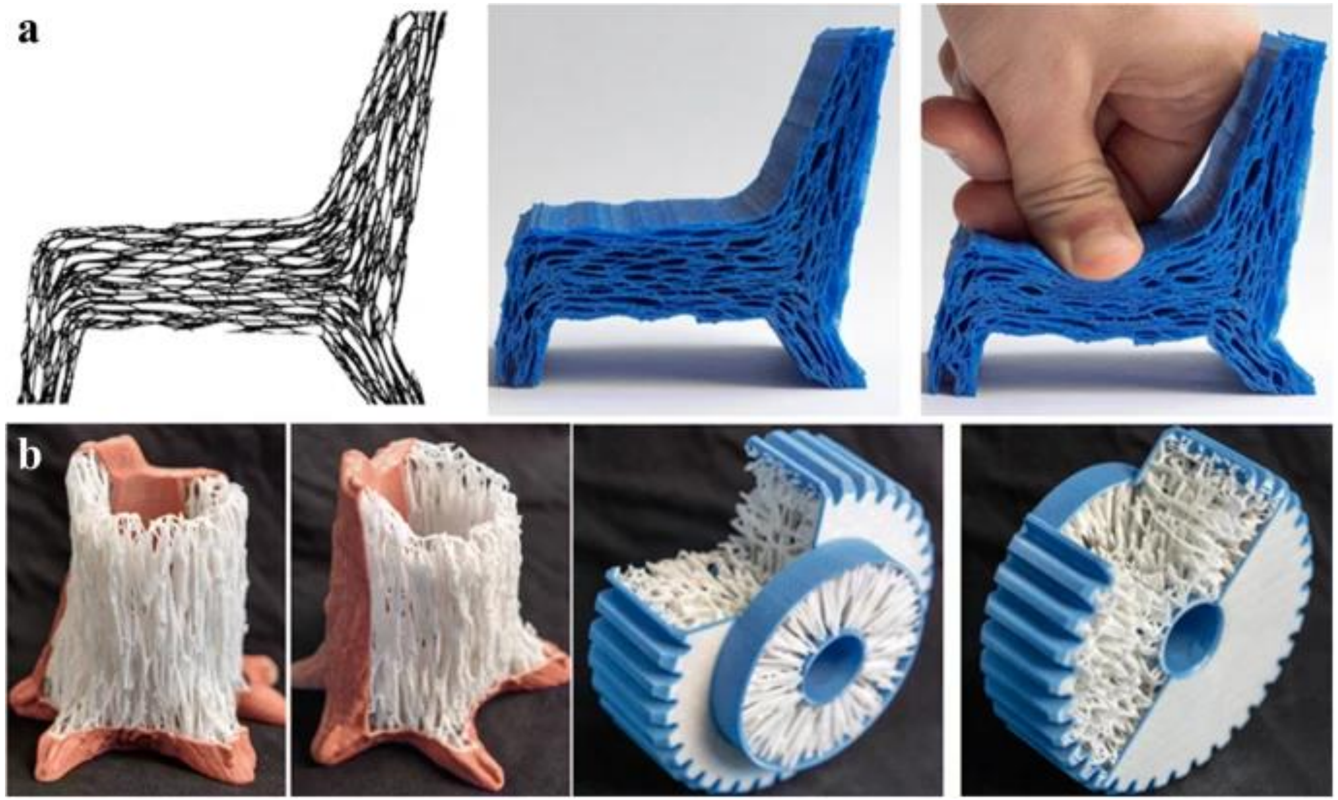
قابلیت‌های AM در طراحی: پیچیدگی

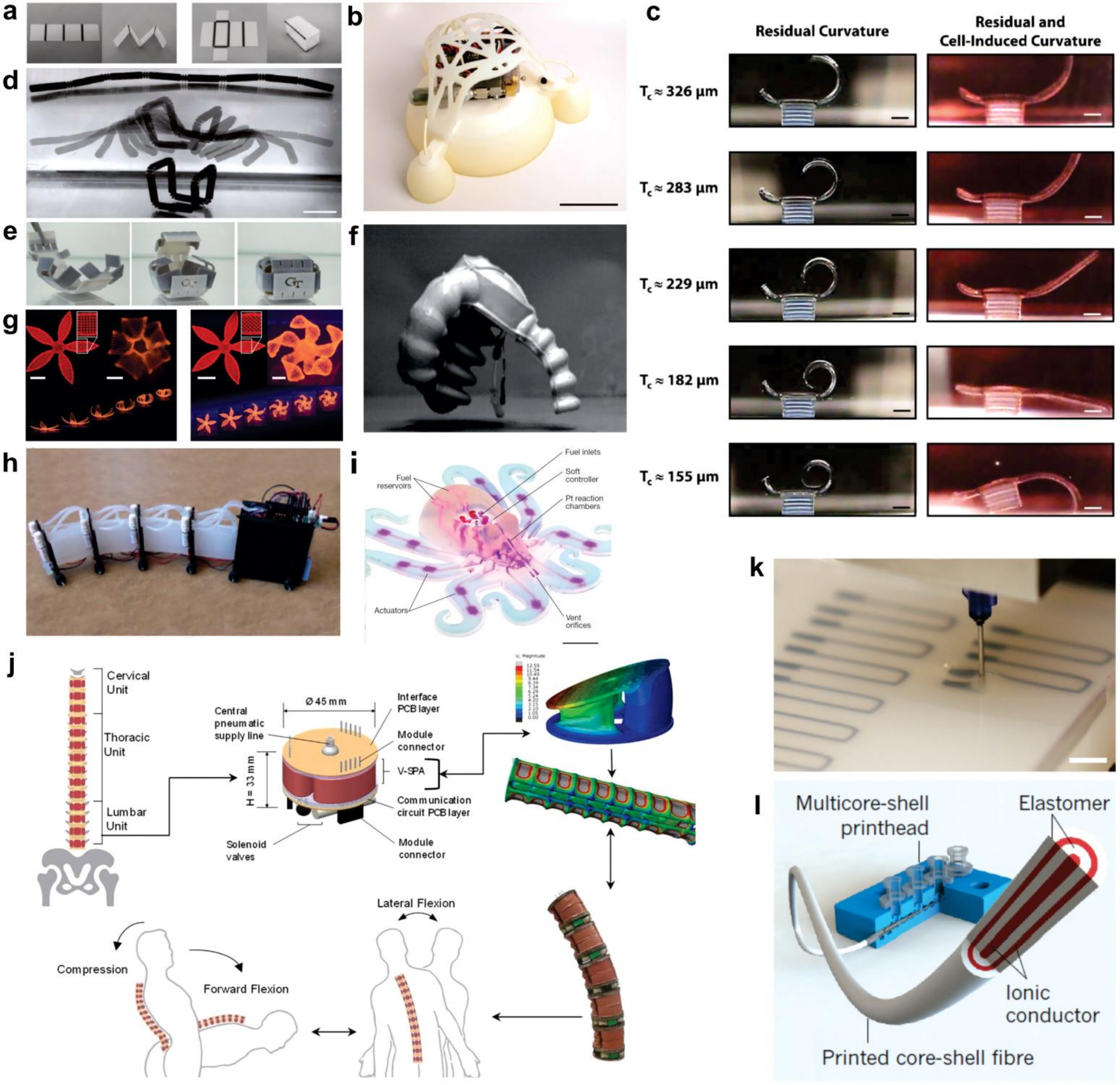
سلسله مراتبی

- در مقیاس ماکرو: جذب انرژی، خواص حرارتی، عایق صوتی،
  افزایش نسبت استحکام به وزن و ...









قابلیت‌های AM در طراحی:

پیچیدگی کاربردی

- امکان تولید محصولات متحرک، مدارها، سنسورها و ... روی قطعات

Figure 1. Examples of printed soft robots and soft devices. (a) Pre-strained polystyrene substrate with inkjet-printed hinges made of carbon black ink. (b) 3D-printed jumping soft robot. (c) 3D stereolithography-printed bat with curvature time lapse. (d) 4D-printed composite with swellableable hinges. (e) 4D-printed unfolded box composed of shape memory polymers. (f) A jumping soft robot with 3D-printed mould. (g) 4D printing of hydrogel composites for soft robotic applications. (h) A snake inspired soft robot with 3D-printed mould. (i) Multi-step 3D-printed octobot. (j) Pneumatic actuator for spinal compression and flextion with 3D-printed mould. (k) Embedded 3D printing of soft strain sensor for soft robots. (l) Multicore print head shell capacitive sensor.

قابلیت‌های AM در طراحی: پیچیدگی موادی

- امکان تولید قطعات چند ماده‌ای، گرادیانی

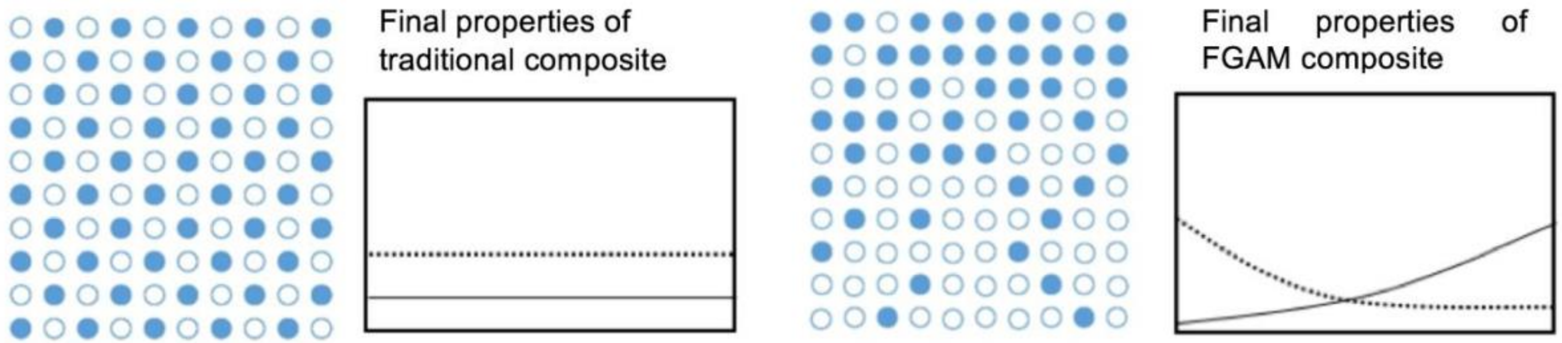
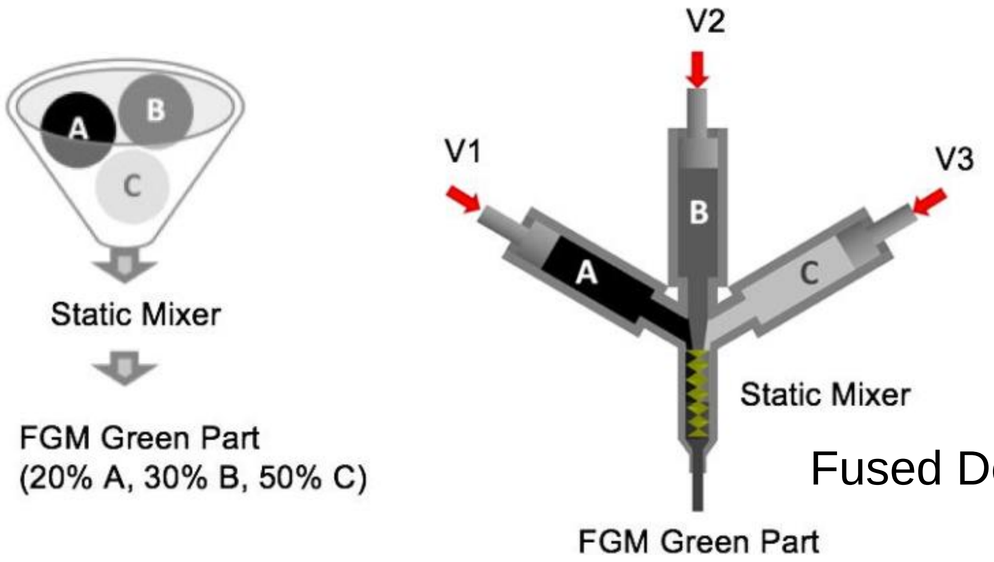


Figure 4: Traditional composite versus FGAM composite and schematic structures to illustrate the change in material properties in thermal conductivity (….) and elastic modulus (–) (Craveiro, et al, 2013).



Fused Deposition Modelling (FDM)

Figure 15: Schematic diagram of a static mixer and triple extruder of FEF system [26].

قابلیت‌های AM در طراحی: پیچیدگی موادی

Selective Laser Sintering (SLS)

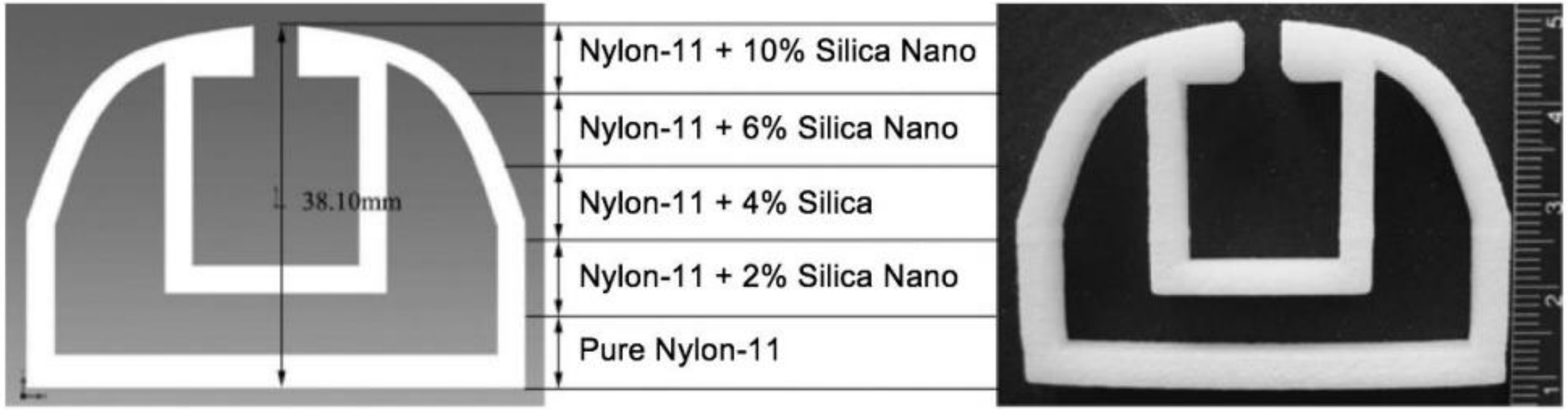
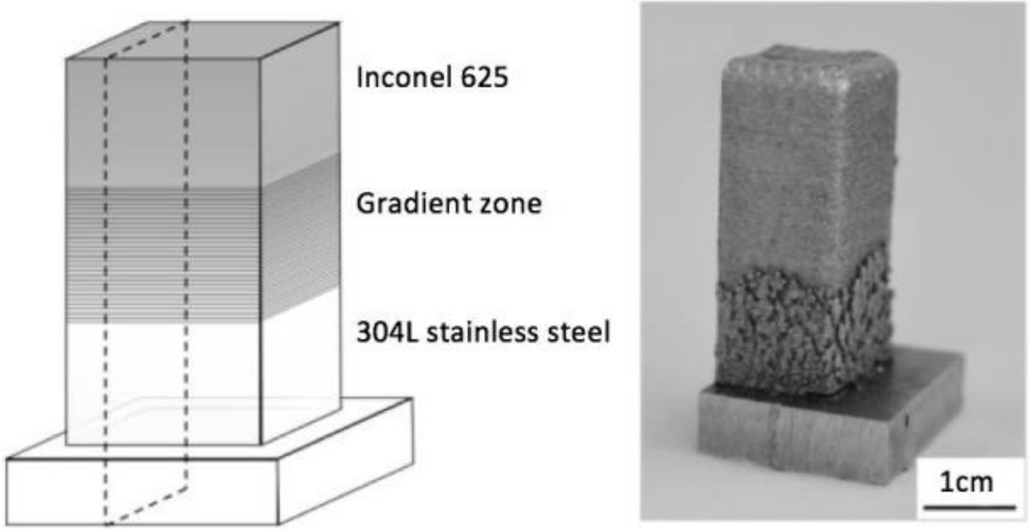


Figure 17: Compliant gripper. 7.62mm each layer [Mumtaz, 2007].

- امکان تولید قطعات چند ماده‌ای، گرادیانی



Laser metal deposition process (LMD)

Figure 20: Schematic and photograph of gradient alloy specimen by Carrol [Caroll, 2016]. The dotted line shows where the part was sectioned for analysis.

قابلیت‌های AM در طراحی: پیچیدگی هندسی

- در برخی از کاربردها مانند تولید بافت پارچه پرینت شده، تعداد سطوح افزایش یافته و نمایش گرافیکی آنها مشکل می‌شود.
- اشغال حجم زیاد و نیاز به حافظه بالا

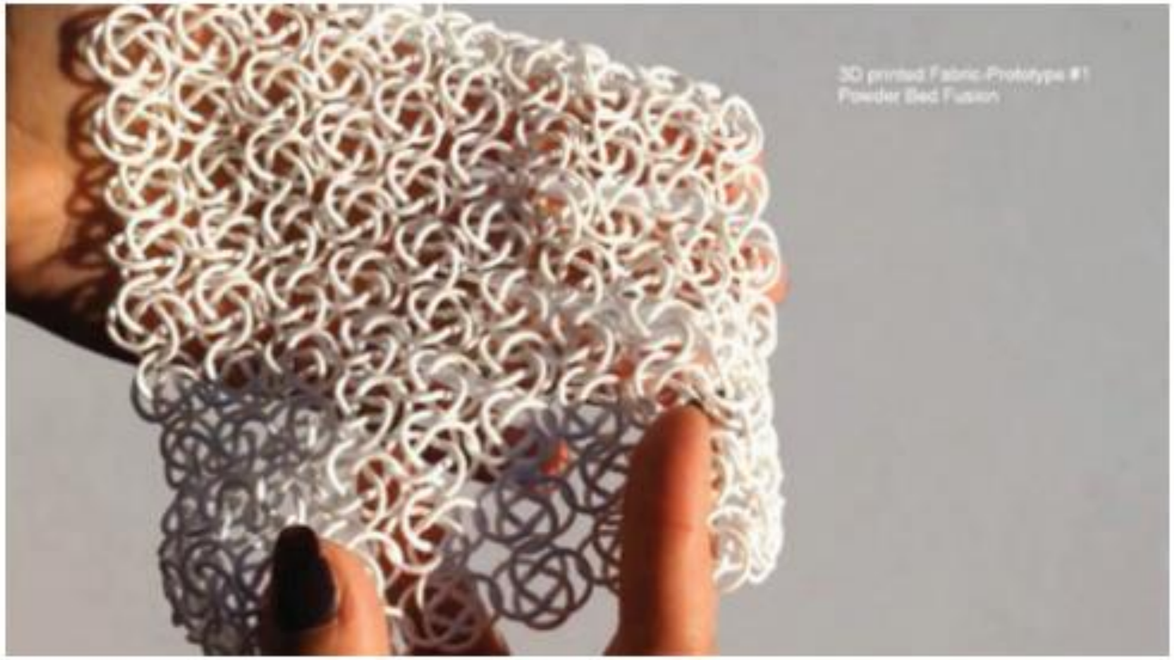
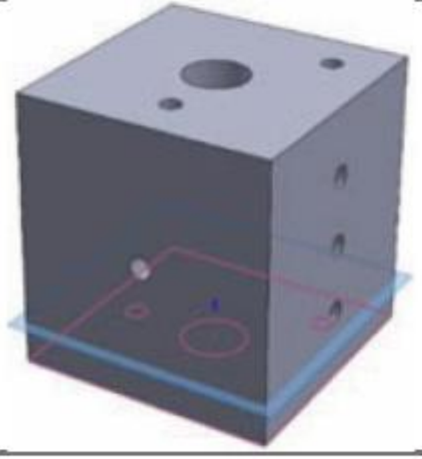
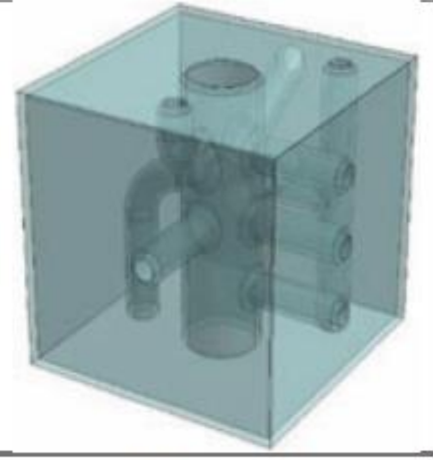


FIG. 1. An example of a chainmail fabric created with traditional 3D printing.[6] Color images available online at www.liebertpub.com/3dp

قابلیت‌های AM در طراحی: **بازطراحی**

- امکان تغییر طراحی تا قبل از شروع ساخت قطعه

			
	منیفولد بلوکی	منیفولد بلوکی تبدیل شده به پوسته	طراحی بهینه‌سازی شده منیفولد برای AM
زمان پیمایش برای الگوی هاشور	۱۹۱ ساعت و ۱ دقیقه و ۳۳ ثانیه	۳۶ ساعت و ۳۱ دقیقه و ۲۱ ثانیه	۱۹ ساعت و ۴۰ دقیقه و ۳۹ ثانیه
هزینه دستگاه در فلز با قیمت ۶۵ دلار در ساعت	۱۲/۴۱۵ دلار	۲،۳۷۹/۰۰ دلار	۱،۲۶۱/۰۰ دلار
وزن مواد	۷/۴۴۱ کیلوگرم	۱/۲۳۲ کیلوگرم	۰/۵۵۸ کیلوگرم
هزینه مواد با احتساب هر کیلو ۷۰ دلار + ۱۰٪ اتلاف	۵۷۰/۶۴ دلار	۹۴/۸۶ دلار	۴۲/۹۶ دلار
بهای رسمی اعلام شده قطعه از جنس فولاد ضد زنگ 316L	۱۵،۲۹۳/۸۲ دلار	۳،۷۳۵/۱۲ دلار	۱،۹۸۶/۲۵ دلار

قابلیت‌های AM در طراحی: طراحی ویژه تجاری

- شخصی سازی محصولات

https://www.sciencedirect.com/science/article/abs/pii/S0007850617301488

انتخاب مواد

Table 1
Current commercial materials directly processed by AM, by AM process category.

	Amorphous	Semi-crystalline	Thermoset	Material extrusion	Vat polymerization	Material jetting	Powder bed fusion	Binder jetting	Sheet lamination	Directed energy deposition
ABS [Acryonitrile Butadiene Styrene]	X			X						
Polycarbonate	X			X						
PC/ABS Blend	X			X						
PLA [Polylactic Acid]	X			X						
Polyetherimide (PEI)]	X			X						
Acrylics			X		X	X				
Acrylates			X		X	X				
Epoxies			X		X	X				
Polyamide (Nylon) 11 and 12		X					X			
Neat		X					X			
Glass filled		X					X			
Carbon filled		X					X			
Metal (Al) filled		X					X			
Polymer bound	X	X		X						
Polystyrene	X						X			
Polypropylene		X					X			
Polyester ("Flex")							X			
Polyetheretherkeytone (PEEK)		X		X			X			
Thermoplastic polyurethane (Elastomer)				X			X			
Chocolate		X		X						
Paper									X	
Aluminum alloys							X	X	X	X
Co–Cr alloys							X	X		X
Gold							X			
Nickel alloys							X	X		X
Silver							X			
Stainless steel							X	X	X	X
Titanium, commercial purity							X	X	X	X
Ti–6Al–4V							X	X	X	X
Tool steel							X	X		X

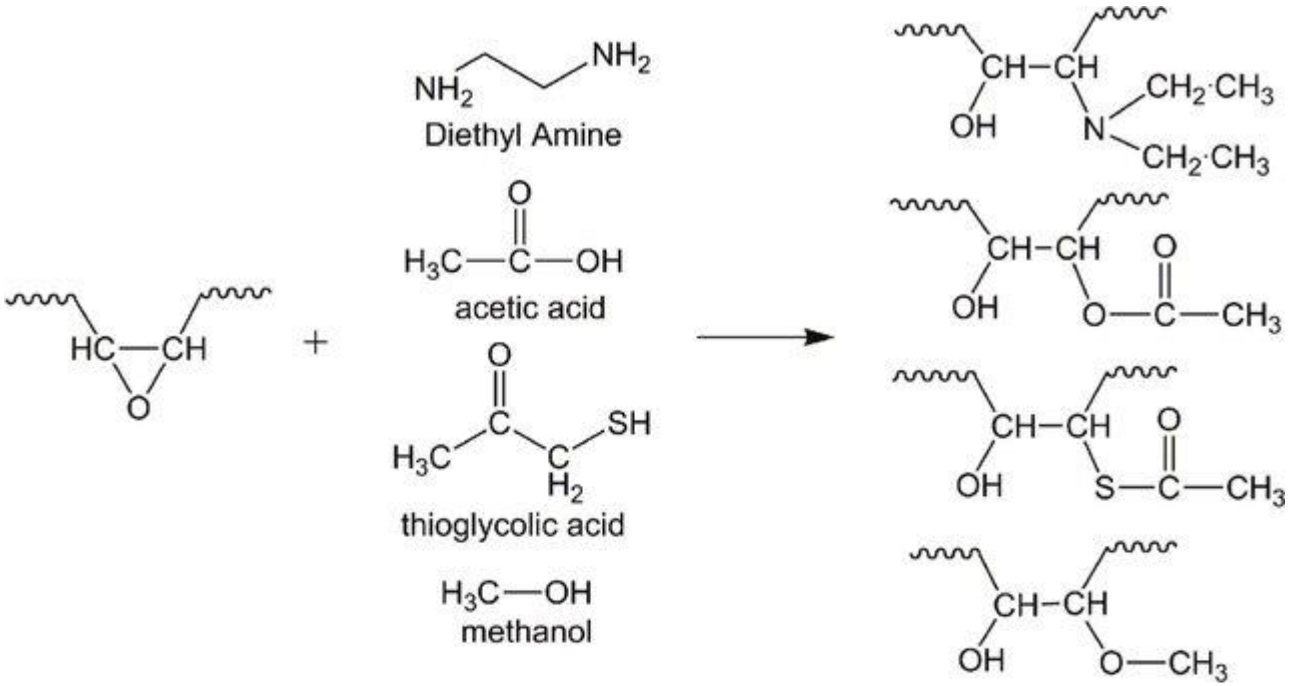
Thermosets

- Typical photopolymers are composed of monomers, oligomers, photoinitiators, and a variety of other additives including inhibitors, dyes, antifoaming agents, antioxidants, toughening agents, etc.
- The first photopolymers used in **vat photopolymerization** were **mixtures** of **UV photoinitiators** and **acrylate monomers** [146].
- **Vinylethers** were another class of monomers that were used in early resins.
- **Acrylate** and **vinylether** resins exhibited **considerable shrinkage**, from **5 to 20%**, which caused **residual stresses** to accumulate as parts were built layer-by-layer which, in turn, caused significant **warpage**.
- Another **disadvantage** of acrylate resins is that their **polymerization** reactions are **inhibited** by **atmospheric oxygen**.

انتخاب مواد: پلاستیک‌ها

Thermosets

- **Epoxy** monomers have **rings** which, when reacted, **open** to provide sites for other **chemical bonds**. **Ring-opening** is known to impart **minimal volume change**, because the **number and types of chemical bonds** are essentially **identical before and after reaction**. Thus, epoxy SL resins shrink less than acrylates and have much **less tendency to warp and curl**.



انتخاب مواد: پلاستیک‌ها

Thermosets

- Almost all **commercially available SL resins** have **significant amounts of epoxies**.
- The acrylates and epoxies affect each other **physically** during the curing process.
- The **reaction of acrylates** will **enhance the photospeed** and **reduce the energy requirements for the epoxy reaction**.
- The **acrylate exhibits a reduced sensitivity to oxygen in the hybrid system** than in the neat composition due to the **viscosity rise caused by epoxy polymerization**, which may result in reduced diffusion of atmospheric oxygen into the material.

انتخاب مواد: پلاستیک‌ها

Thermosets

- The presence of acrylate monomers may **decrease the inhibitory effect of humidity on epoxy polymerization**.
- The **epoxy** monomer acts as a **plasticizer** during the **early polymerization** of the **acrylate** monomer; As a result, **the acrylate polymerizes more extensively**, resulting in **higher molecular weights** in the presence of epoxy than in the neat acrylate monomer.

انتخاب مواد: پلاستیک‌ها

Thermosets

- Thermoset materials for **jetting** processes have formulations that are described **similarly to vat photopolymerization** formulations.
- The jetting resins are typically formulated to have **viscosities greater than 50 cP at room temperature**, but **below 15–20 cP at an elevated temperature**. Commercially available ink-jet deposition heads are **advertised** as being capable of printing many liquids with **viscosities up to 40 or 50 cP.** However, in practice, the resin should have a viscosity **less than half of the advertised maximum** to ensure **clog-free** operation.

انتخاب مواد: پلاستیک‌ها

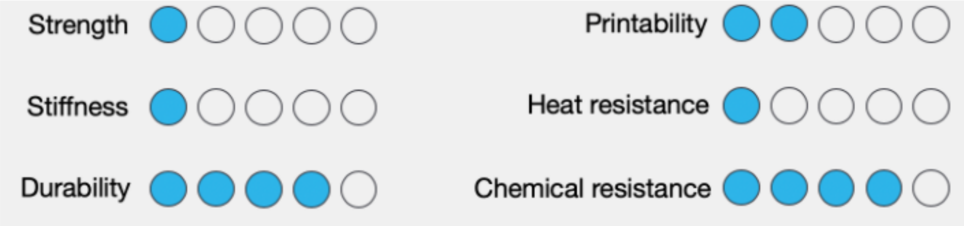
Thermoplastics

- **Material extrusion** and **powder bed fusion** and processes use **thermoplastic** polymers, **amorphous** and **semicrystalline** thermoplastics, respectively.

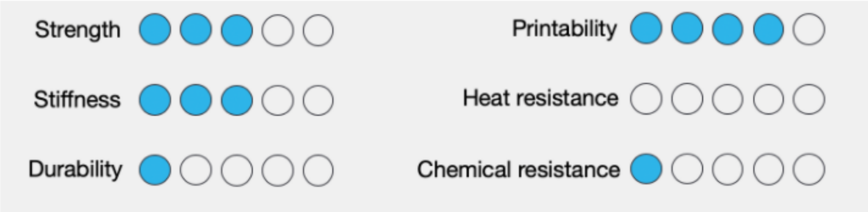
Thermoplastics for Material extrusion (ABS, PLA, …)

- Soften over a wide range of temperature
- Forming a high-viscosity material
- Supports: 1- lattice structure made from the same material,
- 2- using wax-based or poly-vinyl alcohol (PVA) materials

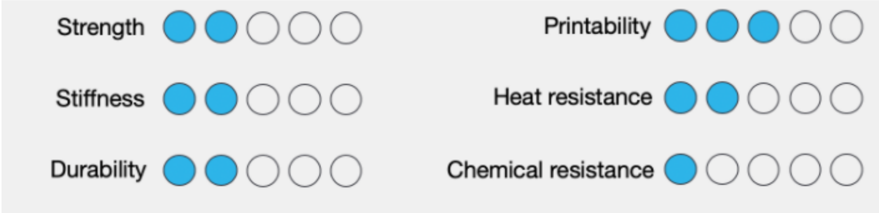
Nylon



PLA



ABS

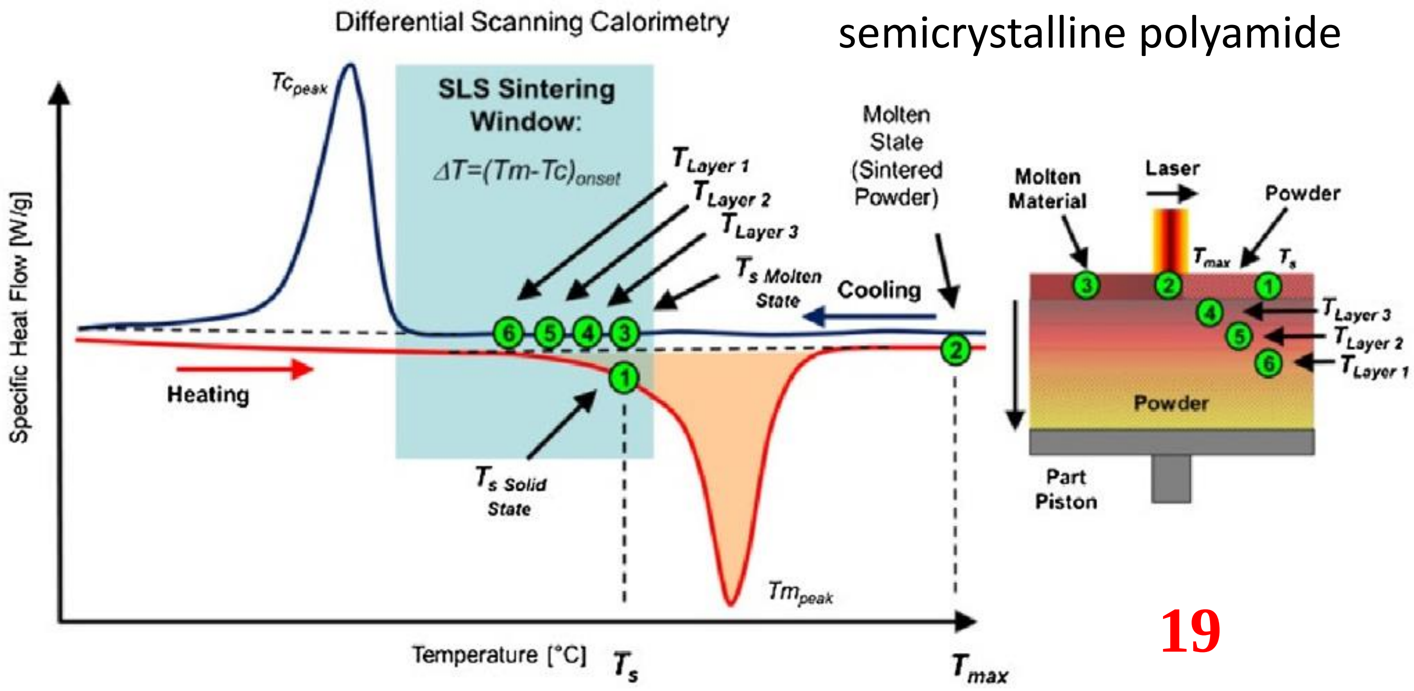


انتخاب مواد: پلاستیک‌ها

Thermoplastics for powder bed fusion (PA12, …)

- The **melting point** is about **35°C higher than the crystallization** temperature.
- The material melted by the laser **remains molten** and in a **thermal equilibrium**
- For liquid pressure tight applications, a post **infiltration** is required.

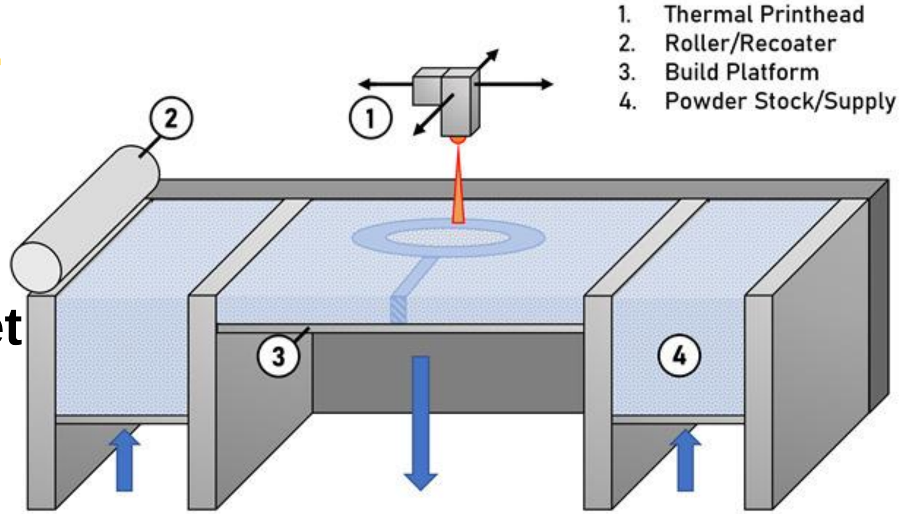
semicrystalline polyamide



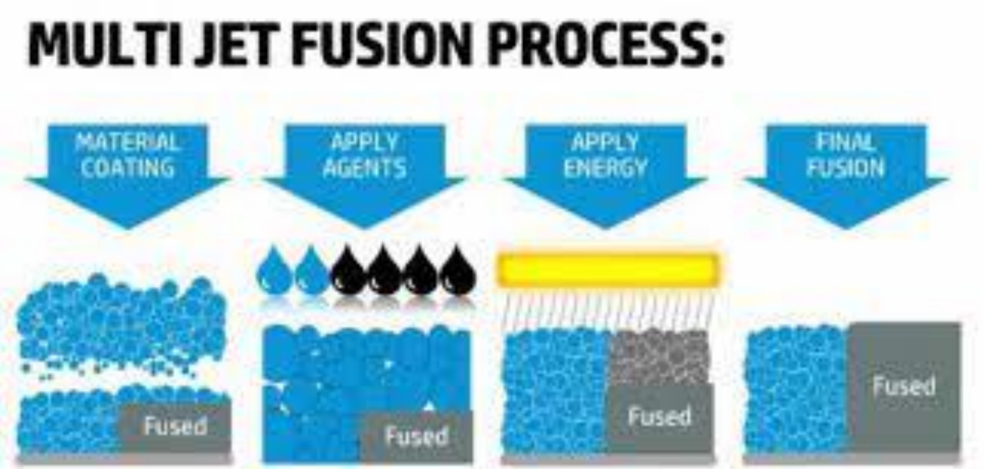
انتخاب مواد: پلاستیک‌ها

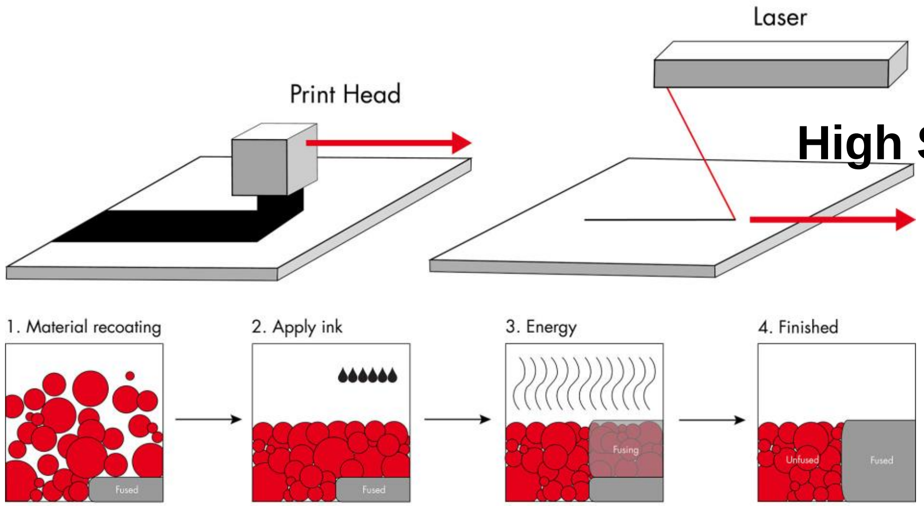
Thermoplastics for powder bed fusion (PA12, …)

- Efforts to increase **productivity**: Replacing the laser as the energy source with a process that **processes the entire layer simultaneously** (**High Speed Sintering and Multi Jet Fusion, Selective Heat Sintering**).



Selective Heat Sintering





High Speed Sintering

انتخاب مواد: فلزات

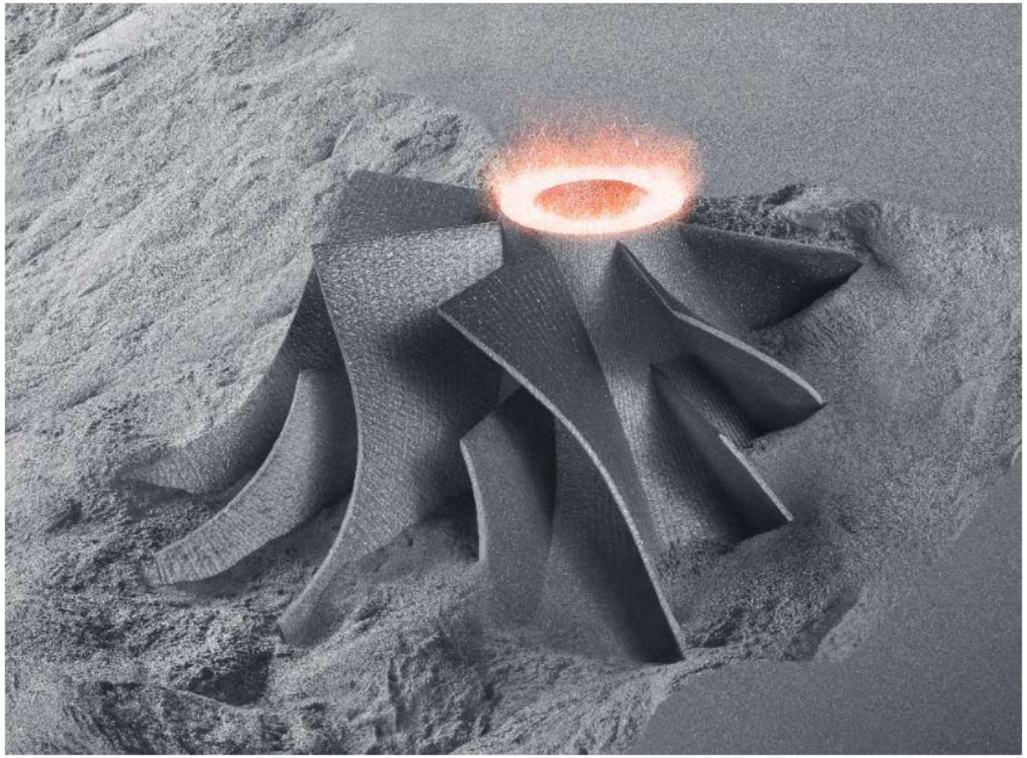
Metals

- **Powder bed fusion** and **directed energy deposition** are the main powder-based AM processes that are **commercially** used to manufacture **quality metal parts**.
- **Metal wire feed DED** and **Binder jetting** are also used to produce metal parts.
- When fusion is involved, the metals generally must be **weldable** and **castable** to be successfully processed in AM.
- The small, moving melt pool is a local hot zone and it is in direct contact with a large and colder area leads to large **thermal gradients** causing significant **thermal residual stresses** and **non-equilibrium microstructures**.

انتخاب مواد: فلزات

Metals

The common **commercially** available alloys are:



- Pure titanium
- Ti6Al4V
- 316L stainless steel
- 17-4PH stainless steel
- 18Ni300 maraging steel
- AlSi10Mg
- CoCrMo
- Inconel 718 and Inconel 625 (nickel based superalloys)
- Precious metals such as gold, silver or platinum (**indirect** processing and also **direct use in SLM**).

انتخاب مواد: فلزات

Metals

Some issues:

- Powder particles of **Al** and **Al alloys** have a **stable Al_2O_3** layer at their surface, **hampering particle sintering** or **melt coalescence**.
- 18Ni300 maraging steel and Inconel 718 form **stable oxides** during processing that **float to the top of the melt pool**.
- Higher levels of **oxygen** in Ti6Al4V **increase the strength** but **reduce the ductility**.
- Creating an **effective melt pool** is difficult for alloys that have a **high reflectivity** (hence low absorption) and **high thermal conductivity**, such as **copper**, **aluminum**, **silver** and **gold**.
- Residual stresses
- Microstructural defects

انتخاب مواد: سرامیک‌ها

Ceramics

- Ceramics, due to their combination of **high melting point** and **low toughness**, are **difficult** to process **directly** in AM.
- In most cases, attempts to **direct** process ceramics have resulted in thermally **induced cracking**.
- Approaches to mitigate cracking include **process optimization**, **adding auxiliary devices** (ultrasonic, thermal, magnetic) and a **doping toughening** approach (ZrO_2 and Y_2O_3 powders).
- **Except DED**, all categories of AM have been utilized in creation of **indirect** AM ceramic parts.

انتخاب مواد: سرامیک‌ها

Ceramics

- **Indirect** AM processing of ceramics requires use of a **binder** in some form that holds the part together after AM.
- Typically, the binder for indirect AM of ceramics is **transient** in nature, being **converted** or **removed** in a **post-processing** step such that the final part is a **neat ceramic** or a **ceramic composite**.
- Ceramic AM parts may be **post-infiltrated** to create **full density parts** instead of **high-temperature furnace post-sintering**.

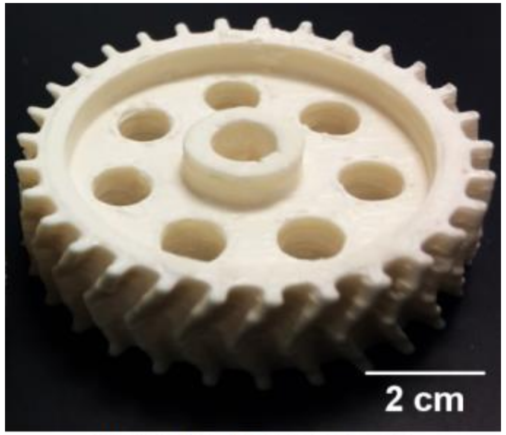


Figure 11. A sintered gear.

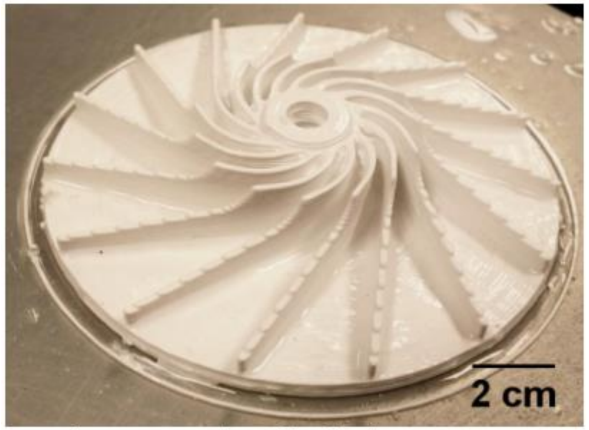


Figure 10. An impeller in the green state.

انتخاب مواد: سرامیک‌ها

Ceramics

Table 6
Additive manufacturing processes and materials for processing ceramics.

AM process	Ceramic binding mechanism	Specific process types	Material	Alumina: reachable density (%) and/or strength (MPa)
Binder jetting	Particulate adhered by adhesive	MIT-based 3D Printing	SiC [188]; Al_2O_3 [188]	–
Directed energy deposition	Melting	LENS	Al_2O_3 [12,176]	Density: up to 98%
Material extrusion	Particulate in slurry binder	FDC, Robocasting, T3DP	SiC [116]; Si_3N_4 [4] [158] [3] [255] [2] [196] [252]; Al_2O_3 [155] [154] [33] [32] [152] [169] [54] [106] [229] [131] [207] [96] [95] [178] [97] [129]; ZrO_2 [61] [72]; ZrC [130]	Density: up to 98%
Material jetting	Particulate in (photo)polymer	Jetting	Al_2O_3 [76]	–
Powder bed fusion	Melting, sintering, transient binder, chemical	SLM, micro SLS, SLS®, SLRS	SiC [253] [57] [58] [230] [231] [164] [199] [200] [60] [233] [23]; Si_3N_4 [24]; SiO2 [237] Al2O3 [49] [234] [222] [48] [47] [223] [125] [124] [11] [138] [235] [236] [265] [79] [268] [118] [117] [69] [84] [85] [199] [200] [60]; ZrO_2 [224] [227] [18] [107]; ZrB_2 [127,128]; [39]	Density: up to 98% Flexural strength: 363 MPa
Sheet lamination	Particulate in binder with adhesive	LOM	Al_2O_3 [73] [75]; ZrO_2 [75]; Si_3N_4 [189] [109] [110] [108]; SiC [279]	Density: up to 99% Flexural strength: 311 MPa
Vat polymerization	Particulate in photopolymer	SLA, Optoforming, LCM	Si_3N_4 [188,280]; Al_2O_3 [280] [37] [267] [1] [28] [88] [266] [27] [218]; ZrO_2 [280]	Density: up to 99.3% 4-pt bending strength: 427 MPa

https://doi.org/10.1016/j.cirp.2016.06.001

انتخاب مواد: کامپوزیت‌ها

Polymer composites

- Feedstock often consists of the **matrix polymer**, **tackifier**, **plasticizer**, **surfactant**, and **secondary phases** such as particulates or fibers of metal, ceramic or polymer composition.
- Tackifiers provide flexibility, plasticizers improve rheology, and surfactants change dispersion character of the secondary phase.
- **Fiber reinforced composites**, usually carbon fiber reinforced composites or fiberglass, vary in mechanical properties depending on orientation of fibers.
- Powder bed fusion, Vat polymerization

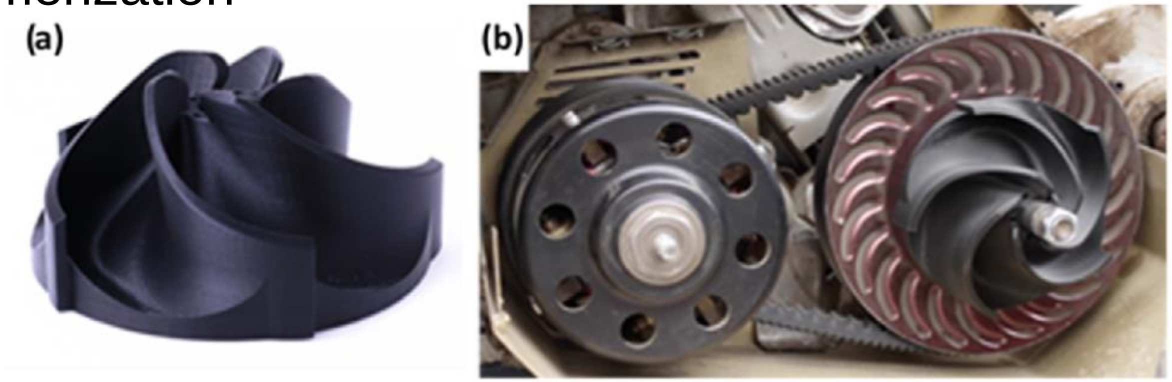


Fig. 11. (a) Chopped micro-carbon reinforced nylon impeller. (b) Engine mounted Onyx impeller in forced-air cooling application [209].

انتخاب مواد: کامپوزیت‌ها

Metal composites

- Metal-matrix composites fabricated using AM include **particulate** composites, **fibrous** composites, **laminates** and **functionally gradient materials** (FGMs).
- **SLM** and laser metal deposition (**LMD**) are highly favored processes for AM of metallic materials.

انتخاب مواد: کامپوزیت‌ها

Metal composites

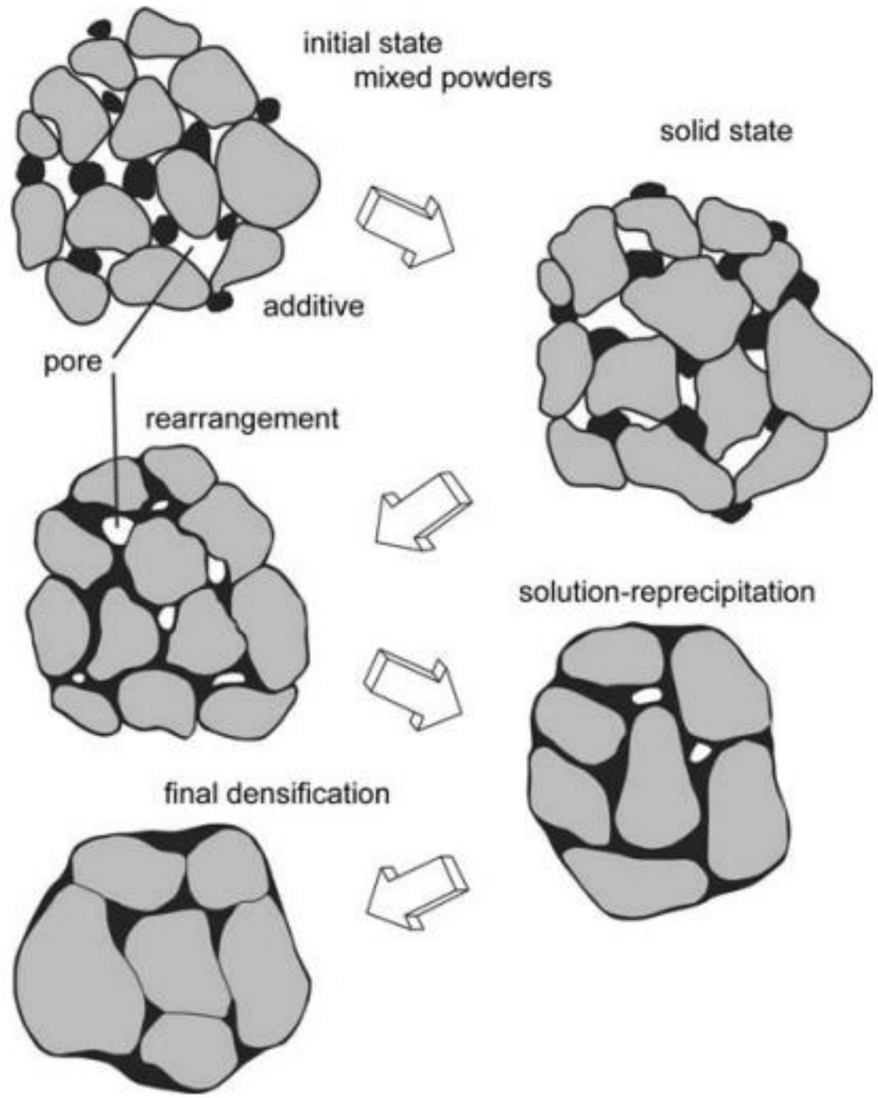
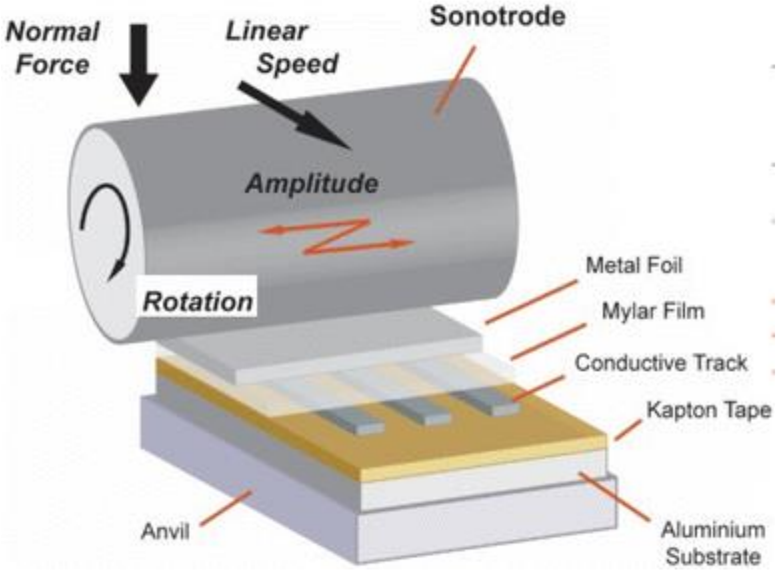


Fig. 1 A schematic of the microstructure changes during LPS, starting with mixed powders and pores between the particles. During heating the particles sinter, but when a melt forms and spreads the solid grains rearrange. Subsequent densification is accompanied by coarsening. For many products there is pore annihilation as diffusion in the liquid accelerates grain shape changes that facilitates pore removal

- It is possible to fabricate metallic composites from powder precursors by **liquid phase sintering (LPS)** to bind the matrix material and secondary phases.
- In the case of WC-Co/Cu composites, with WC particulates reinforcing the Co matrix, **bronze (Cu–Sn)** or **copper additive** is used for LPS.

Metal composites

- **FGMs** have been graded from **metal to metal** and from **metal to ceramic**, using powder precursors (stainless steel to Inconel 625).
- Application of DMD for manufacturing metal matrix composites with ceramic reinforcing phases: e.g. Ti6-4/WC, W-Co cermets, Ti/SiC.
- **Fibers** have been embedded in metal matrices during **the Ultrasonic consolidation** process, making it a strong candidate for fiber reinforced metallic composites (**SiC** fibers in an **aluminum alloy matrix**).



انتخاب مواد: کامپوزیت‌ها

Ceramic matrix composites

- **Biomaterials** is a major area driving AM research and development in AM of ceramics.
- Much like the biopolymer composites, the **bioceramic composites** are **particulates blended** for **homogeneity** and then consolidated via selective laser sintering (**SLS**) or some other AM process.
- **Binder jetting** may also be used to produce other ceramic matrix composites (Si-SiC composites).
- **Stereolithography**: ceramic suspensions (alumina/zinc oxide (Al_2O_3/ZnO) composites).
- **Material jetting:** dielectric ceramic and metal electrodes.
- **Freeze-form extrusion fabrication** (FEF): **graded compositions** from alumina (Al_2O_3) to zirconia (ZrO_2).

Materials for additive manufacturing

Metals and alloys

Main applications
Aerospace and Automotive Military Biomedical

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Nozzle with more than 50 kg.
(Ngo et al., 2018).

Benefits
Mass-customisation Reduced material waste Fewer assembly components Possibility to repair damaged or worn metal parts

Challenges
Limited selection of alloys Dimensional inaccuracy and poor surface finish Post-processing may be required (machining, heat treatment or chemical etching)

Airbus wing brackets (Titanium)

Source: https://3dprintingindustry.com/page/7/?s=brackets (accessed April 25, 2018)

Materials for additive manufacturing (cont'd)

Ceramics

AM produced ceramic functional parts. The turbine wheel diameter is 10 mm (Ligon et al., 2017).

Main applications
Biomedical Aerospace and Automotive Chemical industries

Benefits
Controlling porosity of lattices Printing complex structures and scaffolds for human body organs Reduced fabrication time A better control on composition and microstructure

Challenges
Limited selection of 3D-printable ceramics Dimensional inaccuracy and poor surface finish Post-processing (e.g. sintering) may be required

Materials for additive manufacturing (cont'd)

Concrete

3D printed concrete structure (Ngo et al., 2018).

Main applications
Infrastructure and construction

Benefits
Mass-customisation No need for formwork Less labour required especially useful in harsh environment and for space construction

Challenges
Anisotropic mechanical properties Poor inter-layer adhesion Difficulties in upscaling to larger buildings Limited number of printing methods

Materials for additive manufacturing (cont'd)

Polymers and composites

Main applications
Aerospace and Automotive
Sports
Medical
Architecture
Toys
Biomedical

Introduction to 3D printing technologies: techniques, materials, and applications

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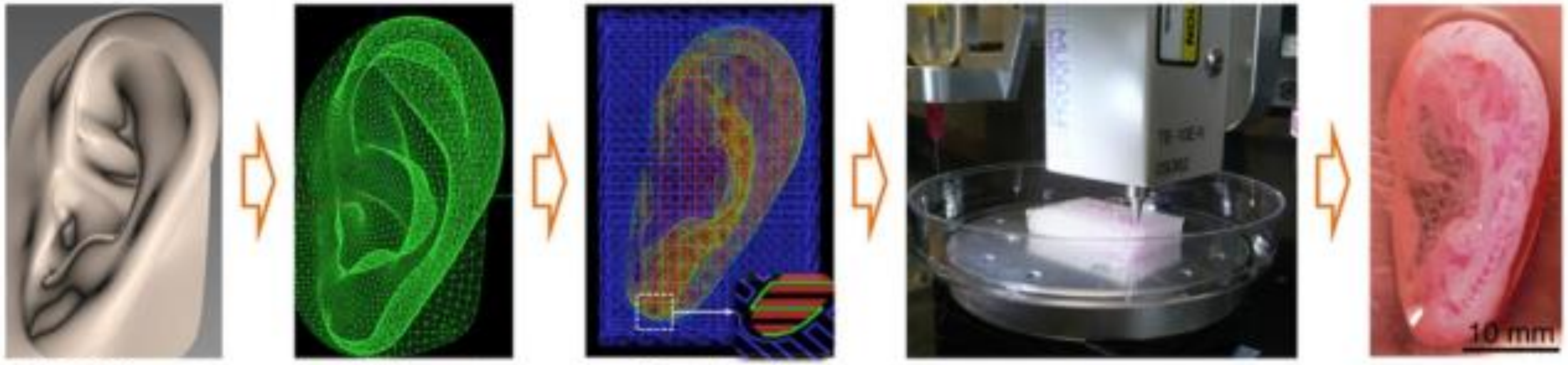

Source: (Lee et al., 2017)

Benefits
Fast prototyping
Cost-effective
Complex structures
Mass-customisation

Source: http://www.3ders.org/articles/20120911-a-list-of-diy-high-resolution-dlp-3d-printers.html (accessed April 25, 2018)

Challenges
Weak mechanical properties
Limited selection of polymers and reinforcements
Anisotropic mechanical properties (especially in fibre reinforced composites)

Materials for additive manufacturing (cont'd)

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Some 3D printed polymer applications

An FFF bracket printed in PLA (grey) showcasing dissolvable PVA support (white)

(Redwood et al., 2017)

3D printing furniture from recycled ABS.

(Ligon et al., 2017)