Semnan University
Additive Manufacturing Laboratory (AML)

آزمایشگاه تحقیقاتی
ساخت افزایشی
دانشگاه سمنان

مباحث منتخب (ساخت افزایشی)

ساخت افزایشی ترکیبی

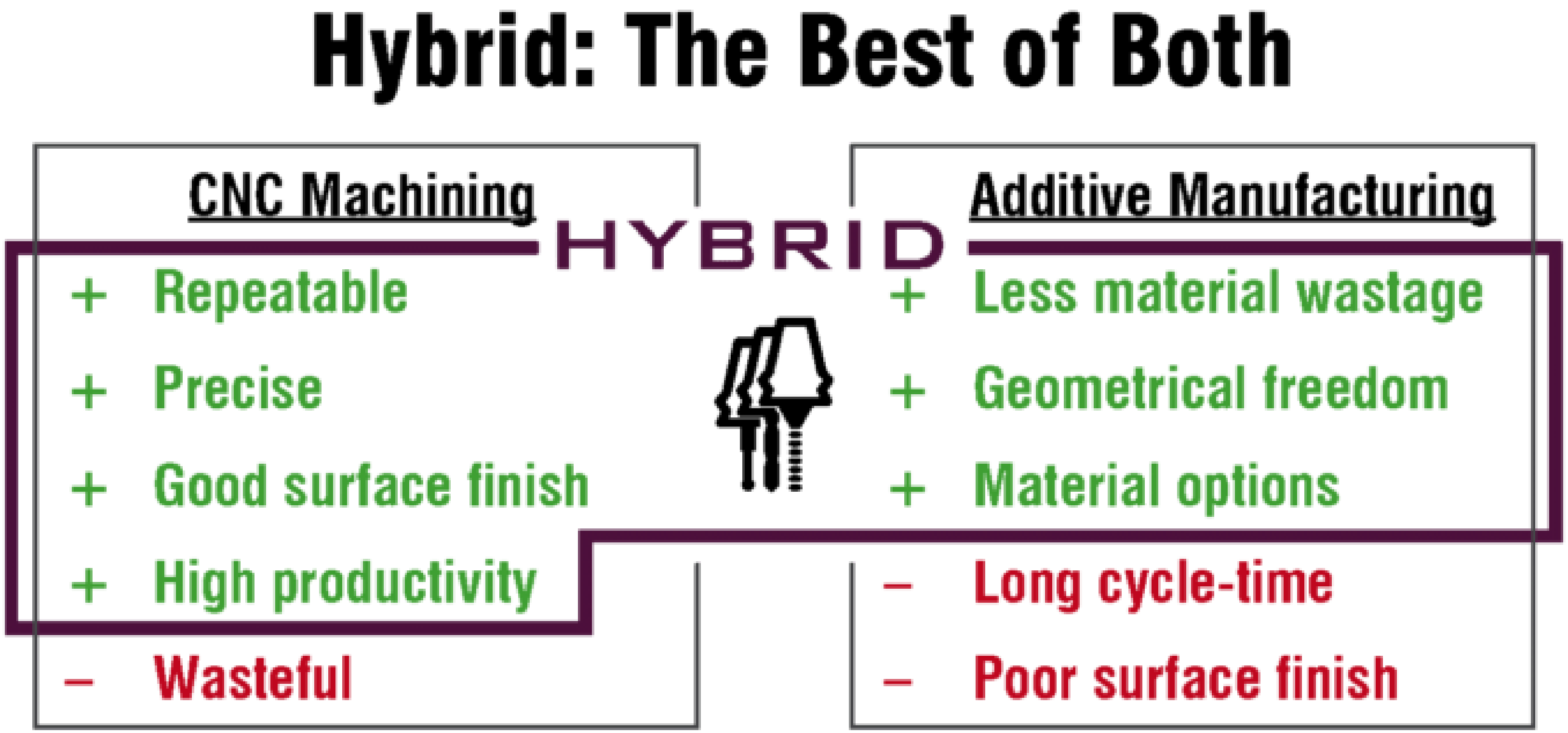
(Hybrid AM)

استاد درس:

دکتر عبدالواحد کمی

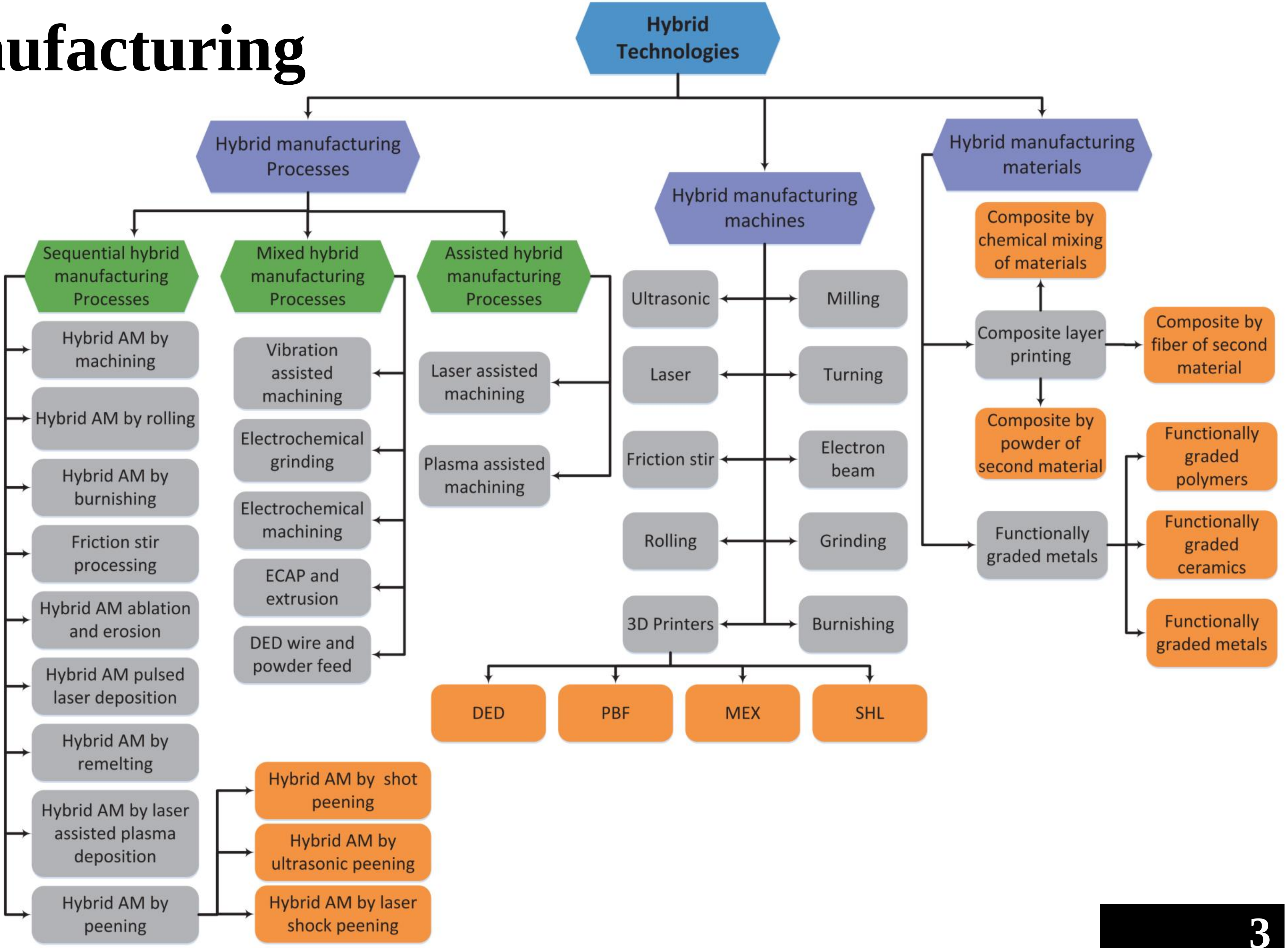
Hybrid Manufacturing (HM)

- Hybrid Manufacturing (HM) has emerged to make **use of the benefits of two or more processes** to obtain desired aspects within **a single workstation** to produce parts with **better quality or lower lead time**.



Hybrid Manufacturing

- HM technologies are divided into **three** main areas including **machines**, **material**, and **processes**.



Hybrid Manufacturing (HM)

- Based on **CIRP**, HM is classified into **assisted** and **mixed** processes.
- In **assisted HM** a **secondary** process **assists** the **primary** process in order to improve the overall manufacturing results. In a **mixed HM** process, the processes **occur simultaneously**.
- The **difference** between assisted and mixed processes is just the **timing.**

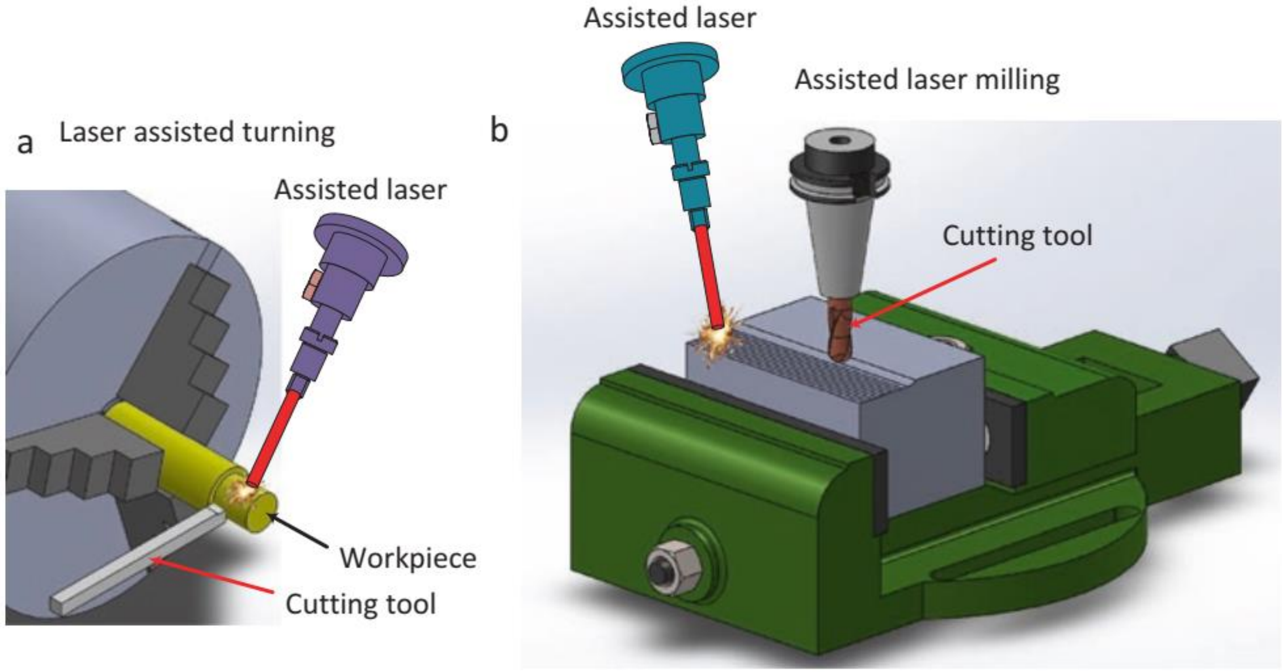


Fig. 12.2 Hybrid assisted manufacturing, (**a**) laser-assisted turning and (**b**) laser-assisted milling [8–12]

Hybrid Manufacturing (HM)

- In mixed HM, the primary and secondary processes happen simultaneously.
- **Vibration-assisted machining**, **electrochemical machining**, **electrochemical grinding**, and **dual powder and wire DED** are all mixed HM methods.
- **Powder** and **wire feed** rates can be controlled **separately** to produce **different volume fractions** of a composite material.

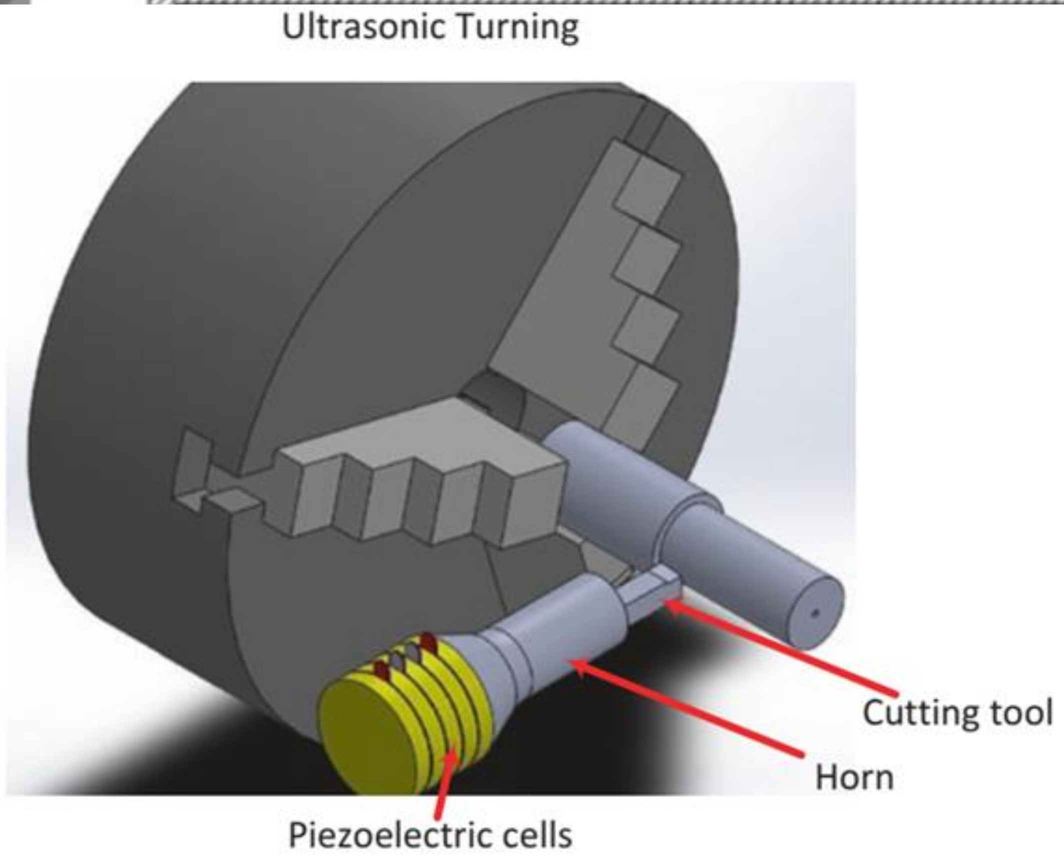


Fig. 12.3 Assisted hybrid manufacturing Ultrasonic Machining (turning)

Hybrid Manufacturing (HM)

- For **fine** detail **powder** is deposited, and for **coarse** features **wire** is deposited.
- As an example, processing **TiC powder** and **Ti-6Al-4V wire** (a uniform distribution of powder particles in the bulk of the material).

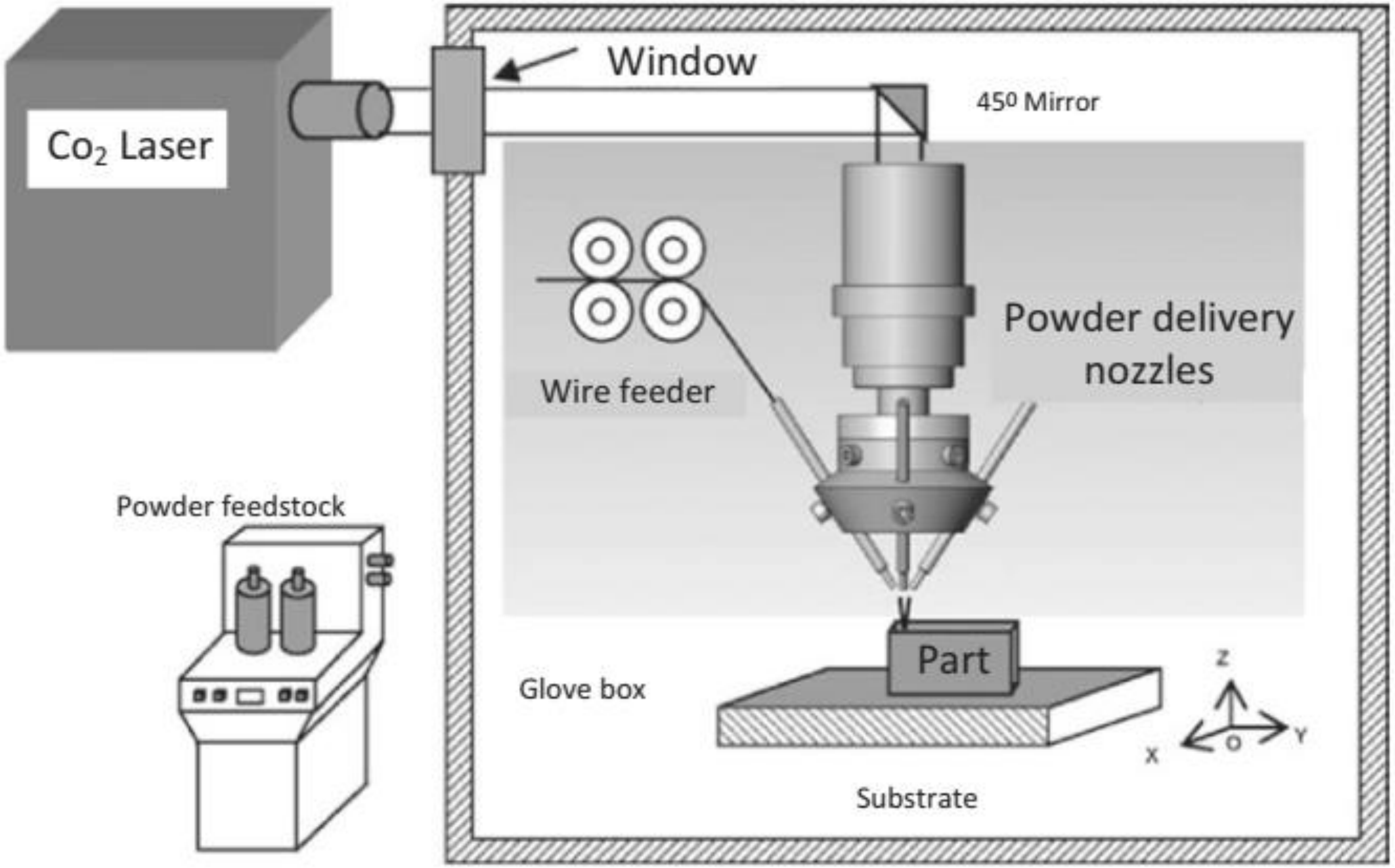


Fig. 12.4 Dual DED powder and wire feed (Elsevier license number: 4687471305451)

Hybrid Manufacturing (HM)

- The most common hybrid AM approach = AM process for creation of a near-net-shape part + machining (to ensure geometric accuracy).
- DMG MORI Lasertec process (combine **DED**, **milling**, and **turning** in a single platform).

Hybrid Additive Manufacturing Principles

1. **Inseparable Hybrid Processes:**
   - The secondary and primary (AM) processes cannot be separated.
   - *Example*: an AM process with a milling process to following the deposition of each layer
   - **Post-processing** such as machining after the AM part is completed, and **preprocessing** such as preheating is **not included**.
2. **Synergy in Hybrid AM:**
   - The secondary process can be applied either **simultaneously** or in a **cyclic** manner (after deposition of one or more layers)
   - **Most** of the hybrid AM processes are **cyclic-based**
   - A simultaneous process example: **laser** assistance during **Plasma Arc AM** (PAAM).

Hybrid Additive Manufacturing Principles

3. <u>**Hybrid Materials:**</u>

- A combination of two or more materials (having different **physical**, **chemical**, and/or **mechanical** properties). → **Composites** & **FGMs**

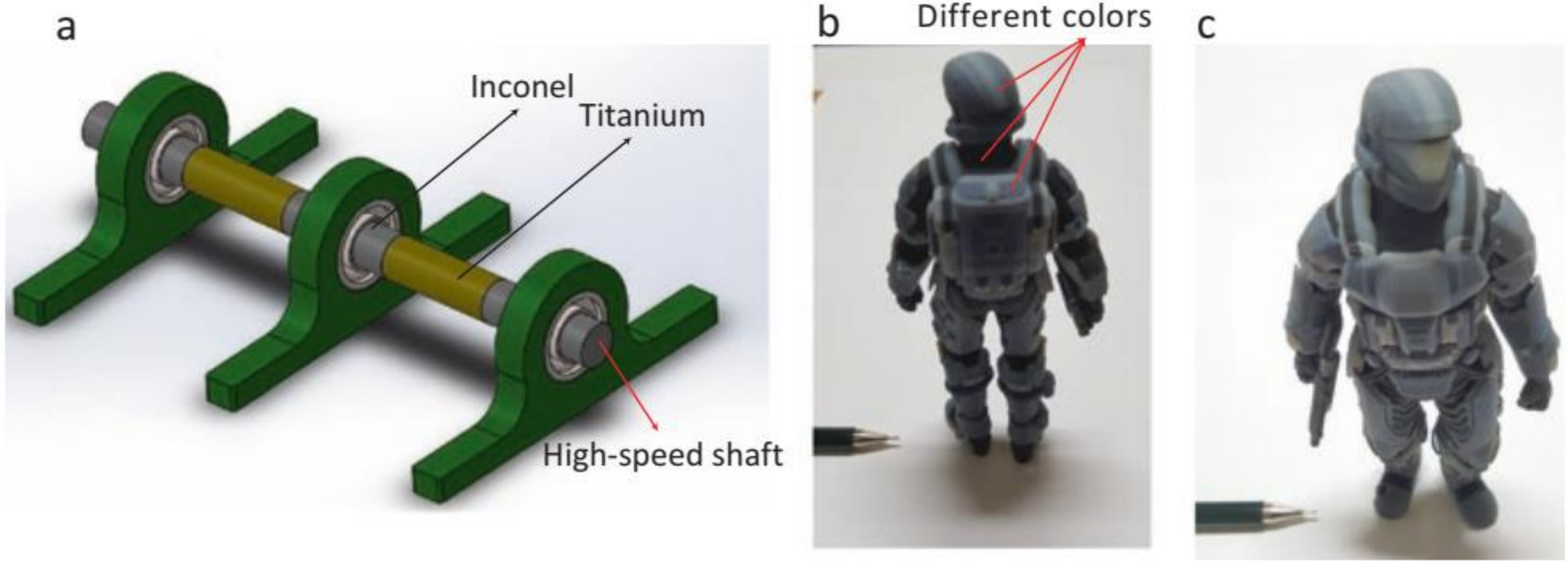


Fig. 12.5 Application for hybrid material (**a**) high-speed shaft made by Inconel and titanium (**b**) figurine made using different material mixtures

Hybrid Additive Manufacturing Principles

4. **Part Quality** and **Process Efficiency:**
   - Part quality and the process efficiency are **often improved**.
   - These improvements related to **tailoring** the **mechanical properties**, **surface enhancements**, and **reducing dimensional deviations**.
   - In most hybrid AM (except in simultaneous hybrid AM), the secondary process **does not assist** the primary build process.
   - *Example*: in hybrid AM using subtractive machining, the material removal process has **no effect** on the build rate, but it does **affect** the overall **time**.

Sequential Hybrid AM Classification

- Hybrid AM processes are **categorized** based upon the **secondary process**.
- In general **secondary process** are designed to provide **surface enhancements**.
- These surface enhancements can be used to increase **accuracy** or change **residual stress** by material removal or to enhance properties such as **hardness**, **corrosion resistance**, and more by processes such as **rolling** and **peening**.

Sequential Hybrid AM Classification

Fig. 12.6 Secondary hybrid AM processes

Sequential Hybrid AM Classification: Machining

- PBF, DED, and SHL + machining
- **Sidewall machining**: the objective is typically to improve **final surface finish** and **dimensional accuracy**.
- **Face machining:** the objective is typically to make a **proper surface for the next layer**.
- The **chips** produced during the machining may interfere with and/or become trapped within subsequent layers.

Sequential Hybrid AM Classification: Machining

- **DED** is the **most commonly** reported process for hybrid systems.
- DMG Mori (LASERTEC), Coherent Laser’s Creator, Matsuura (Avance-25)

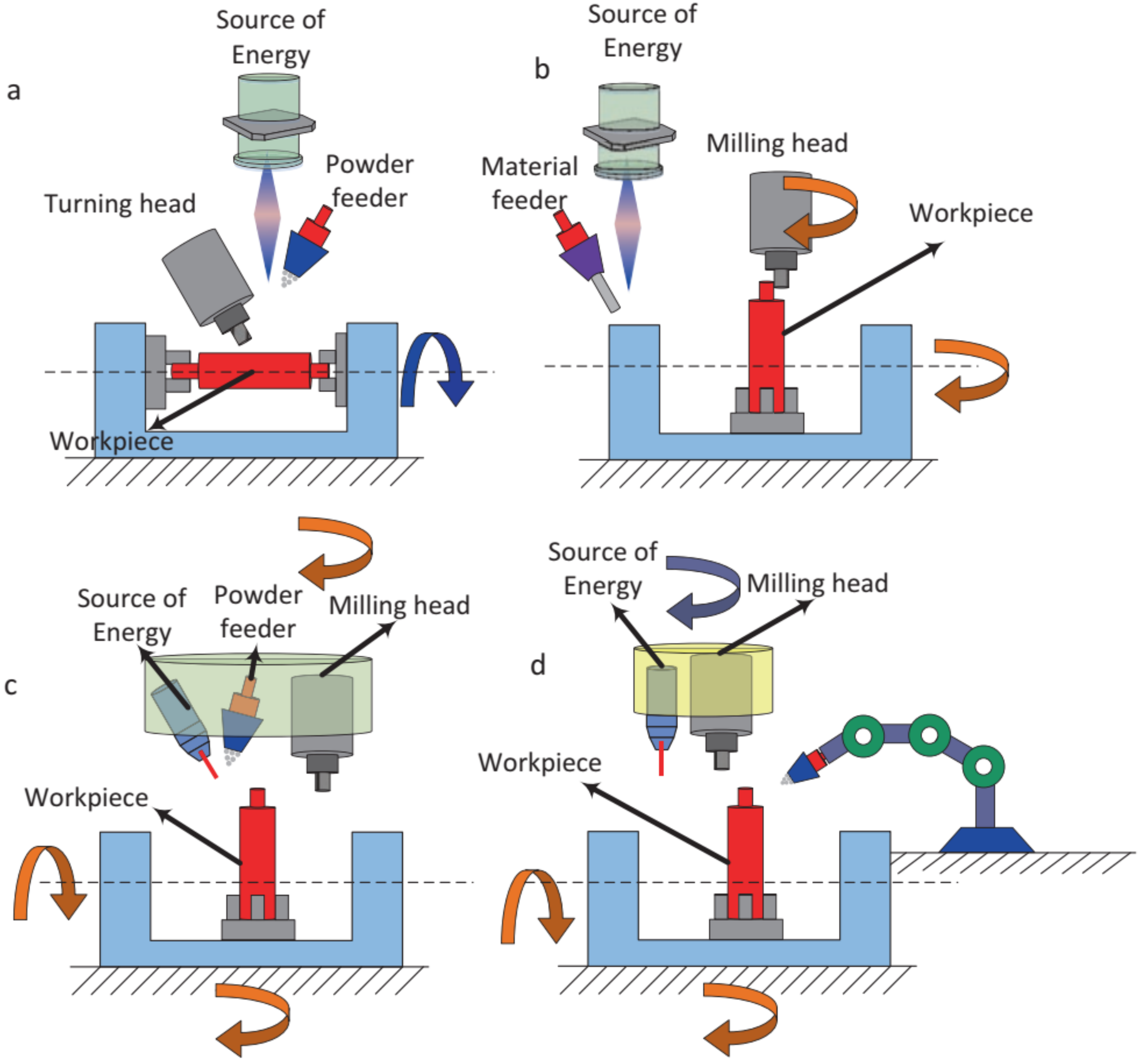


Fig. 12.7 Hybrid DED by machining, (**a**) turning with PAAM, (**b**) multi-axis milling with PAAM (**c**) integrated laser powder head DED with multi-axis milling, and (**d**) separate laser and powder head DED with multi-axis milling

Sequential Hybrid AM Classification: Rolling

- Rolling <u>between</u> layers and/or <u>after (?)</u> completion of the entire component
- Rolling can improve **bonding** and reduce **surface waviness** between deposits within a layer without producing **chips** (unlike machining).
- Smoothing overlapping regions reduces defects such as **keyholes**, **porosity**, and **cracks**.

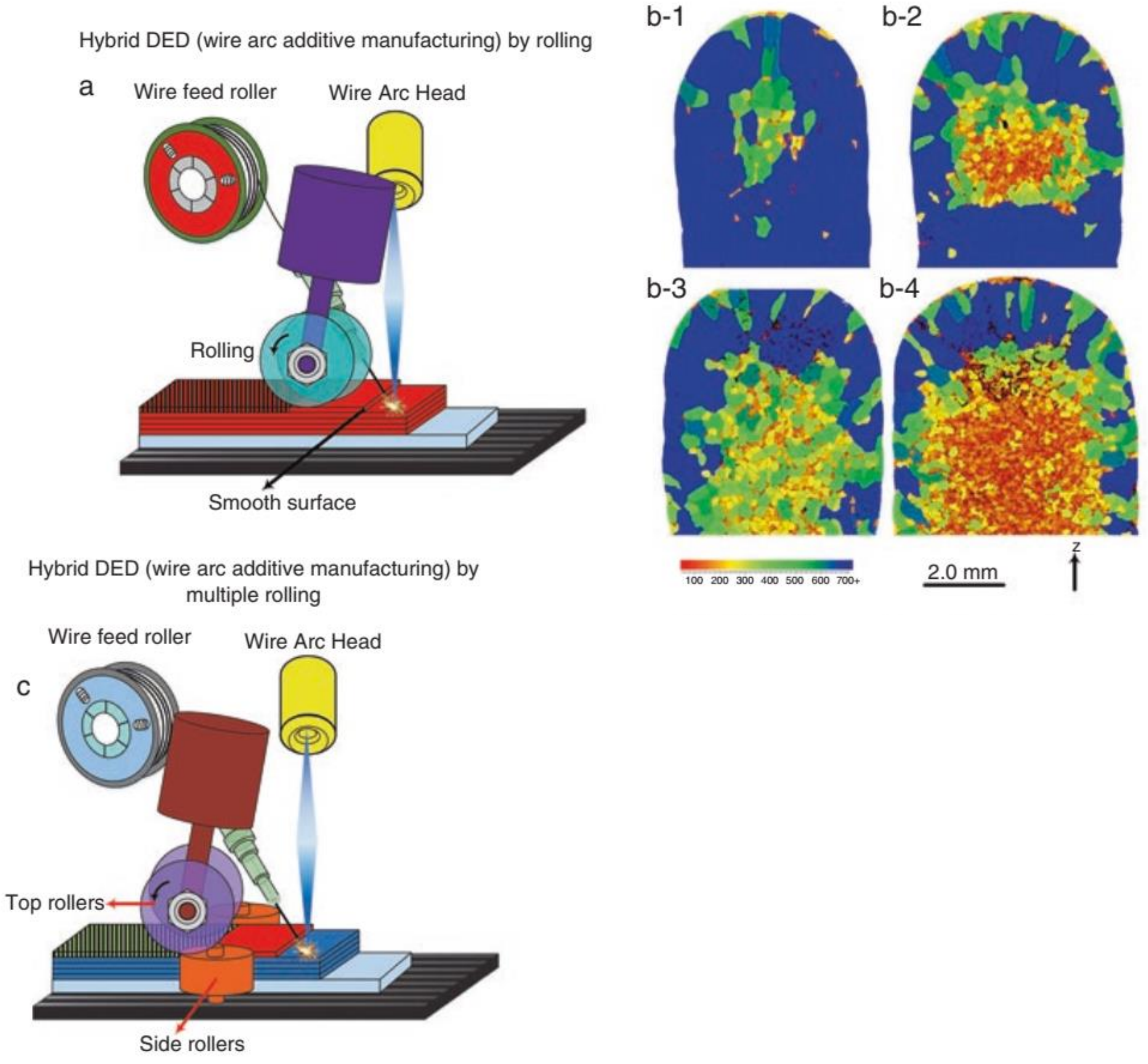


Fig. 12.8 (**a**) Hybrid AM by rolling; (**b**) EBSD reconstructed β grain size maps from Ti-6Al-4V rolled WAAM walls, (**b**-1, **b**-2) single roll pass with 50kN and 75kN loads, and (**b**-3, **b**-4) multiple rolling pass after deposition of each layer with 50kN and 75kN loads [35]; (**c**) multiple pass rolling; and (**d**) hybrid AM by burnishing

Sequential Hybrid AM Classification: Rolling

- Rolling can **relax surface residual stresses** (especially for thermal-based AM processes).
- **Tailored grain structure** and **mechanical properties**, **decreasing distortion** and **increasing dimensional accuracy**.
- **Single** or **multiple** rolling passes (better mechanical properties by multiple pass rolling)
- High temperature rolling (producing refined grain structure and improved mechanical properties).

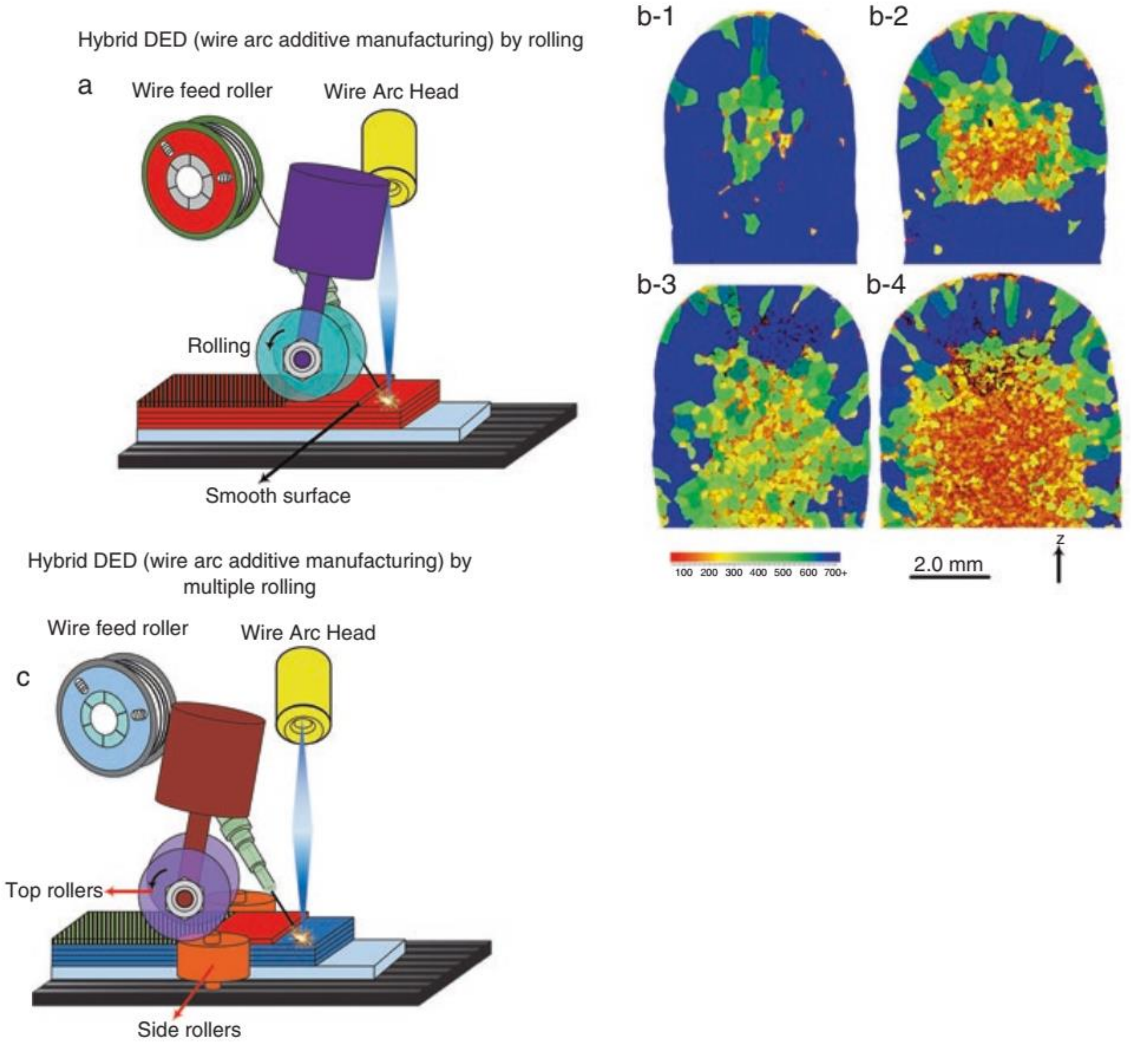
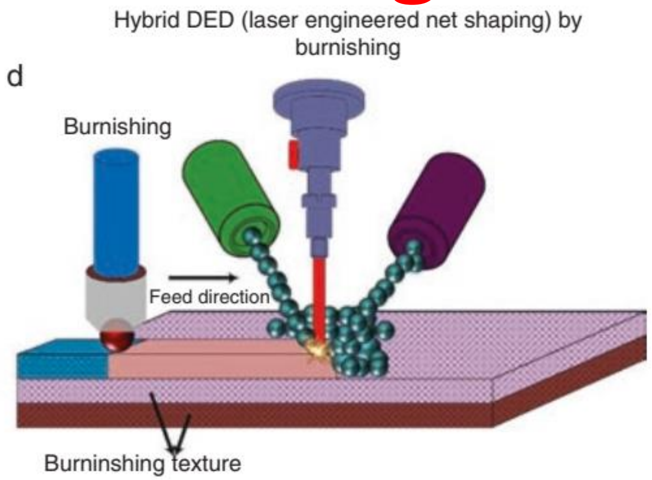


Fig. 12.8 (**a**) Hybrid AM by rolling; (**b**) EBSD reconstructed β grain size maps from Ti-6Al-4V rolled WAAM walls, (**b**-1, **b**-2) single roll pass with 50kN and 75kN loads, and (**b**-3, **b**-4) multiple rolling pass after deposition of each layer with 50kN and 75kN loads [35]; (**c**) multiple pass rolling; and (**d**) hybrid AM by burnishing

Sequential Hybrid AM Classification: Burnishing



- Burnishing is a (cold) surface treatment by **plastic deformation** using sliding contacts such as by **balls** and **cylinder.**
- It improves **surface finish**, refines **microstructure**, and improves **residual stress** and **hardness**.
- **Higher affected depth & rougher surfaces** than rolling (due to the high pressure of burnishing)

Sequential Hybrid AM Classification: FSP

- FSP improves **bonding of layers**, **mechanical properties** and **refinement in grain size**.

https://www.emerald.com/insight/content/doi/10.1108/RPJ-03-2015-0038/full/html

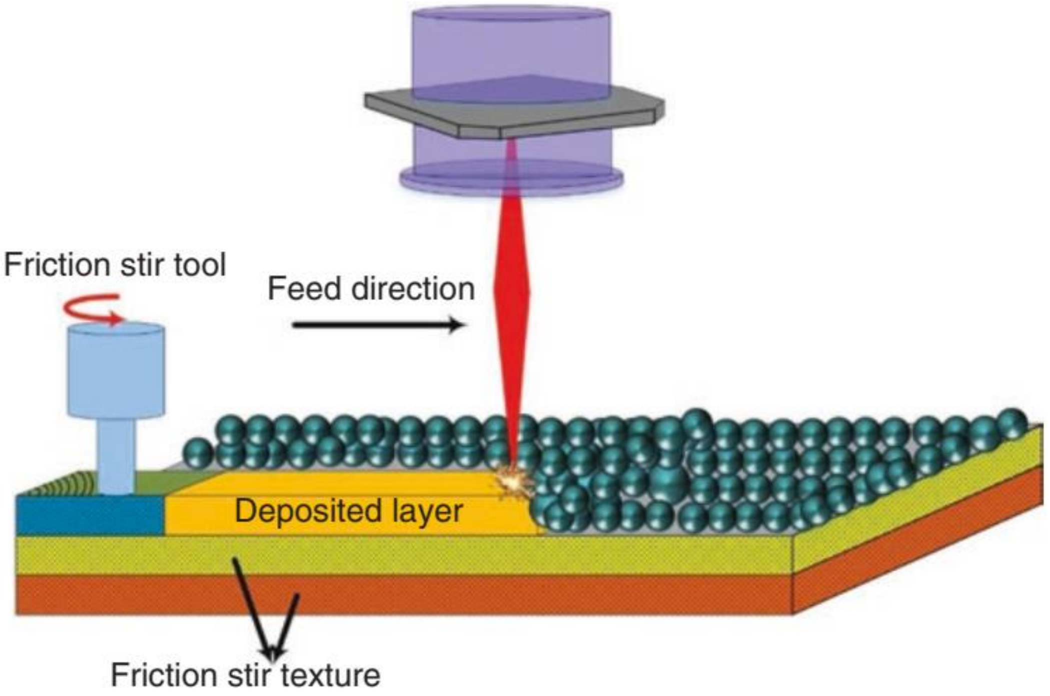
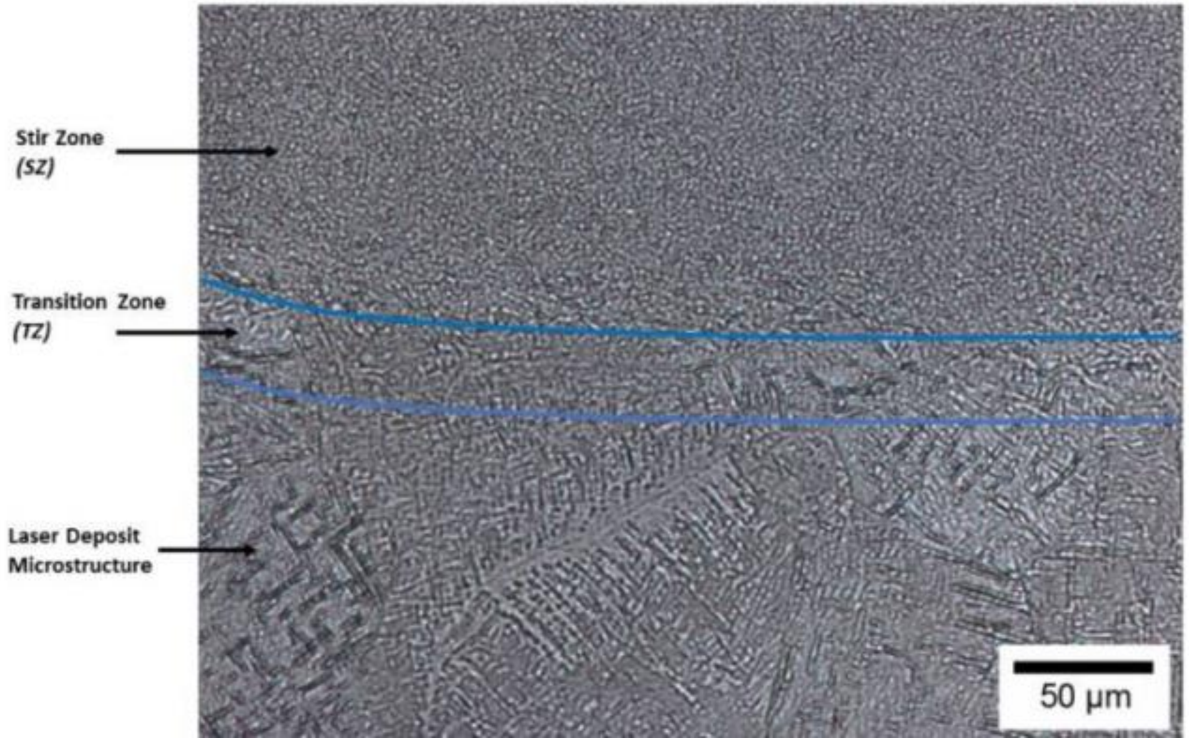


Fig. 12.9 Hybrid Electron Beam Powder Bed fusion (EB-PBF) by friction stir processing



Sequential Hybrid AM Classification: Ablation/Erosion

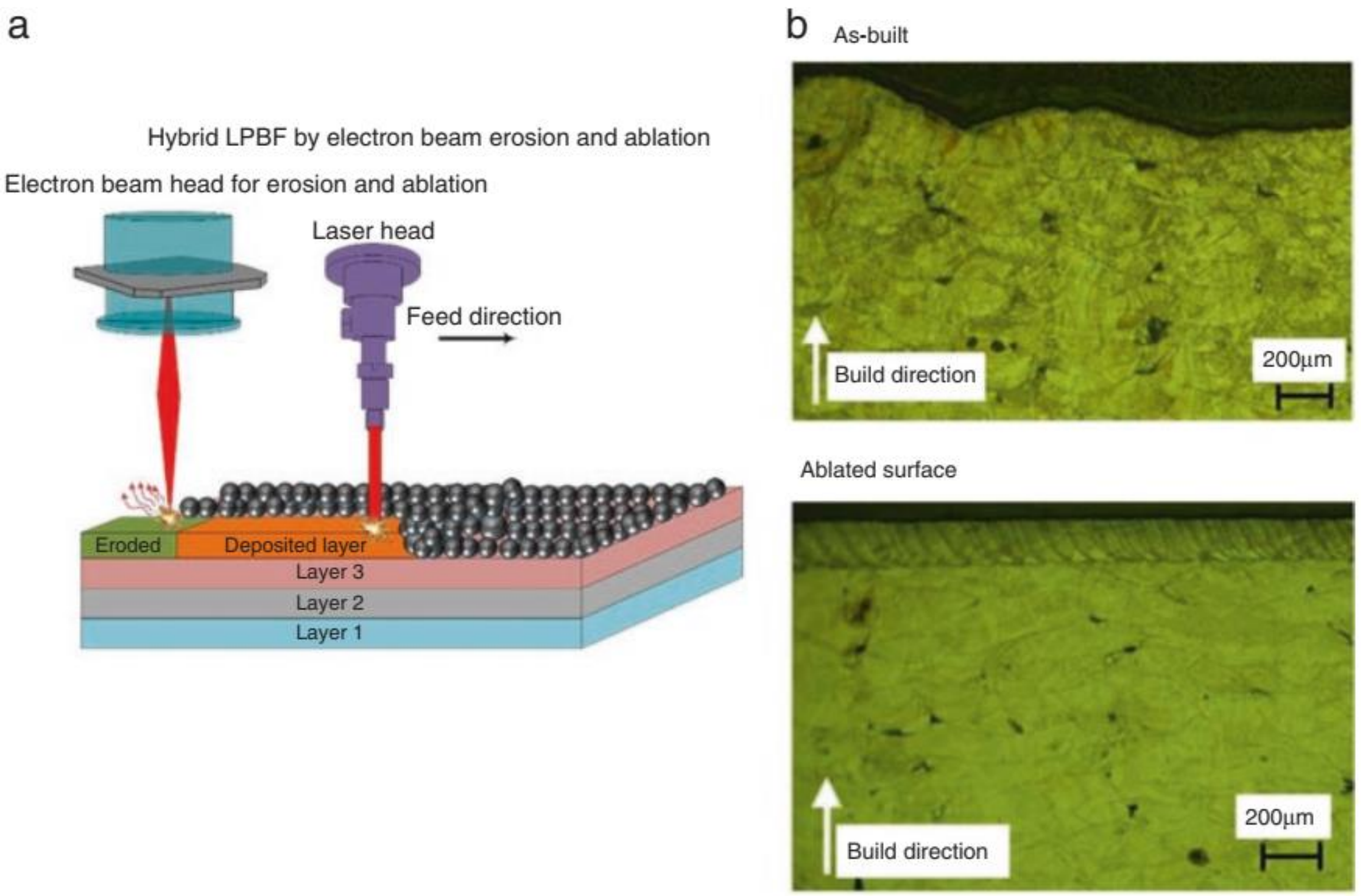
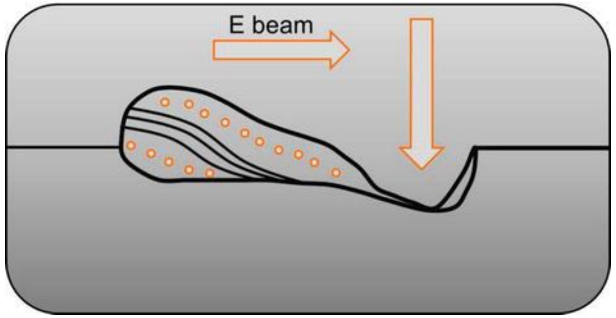


Fig. 12.10 Hybrid LB-PBF by electron beam erosion and ablation (**b**) SEM image of as-built and ablated material (Elsevier license number 4630720259893) [38]



- The deposited layer is eroded or ablated by **electron beam** or **laser**.
- A thin layer is subtracted to produce a smooth and precise cut (improves the **surface quality**, increases **density**, and can produce features with **50–100 µm accuracy**).
- **Noncontact** subtractive process (compare with machining)

Sequential Hybrid AM Classification: Ablation/Erosion

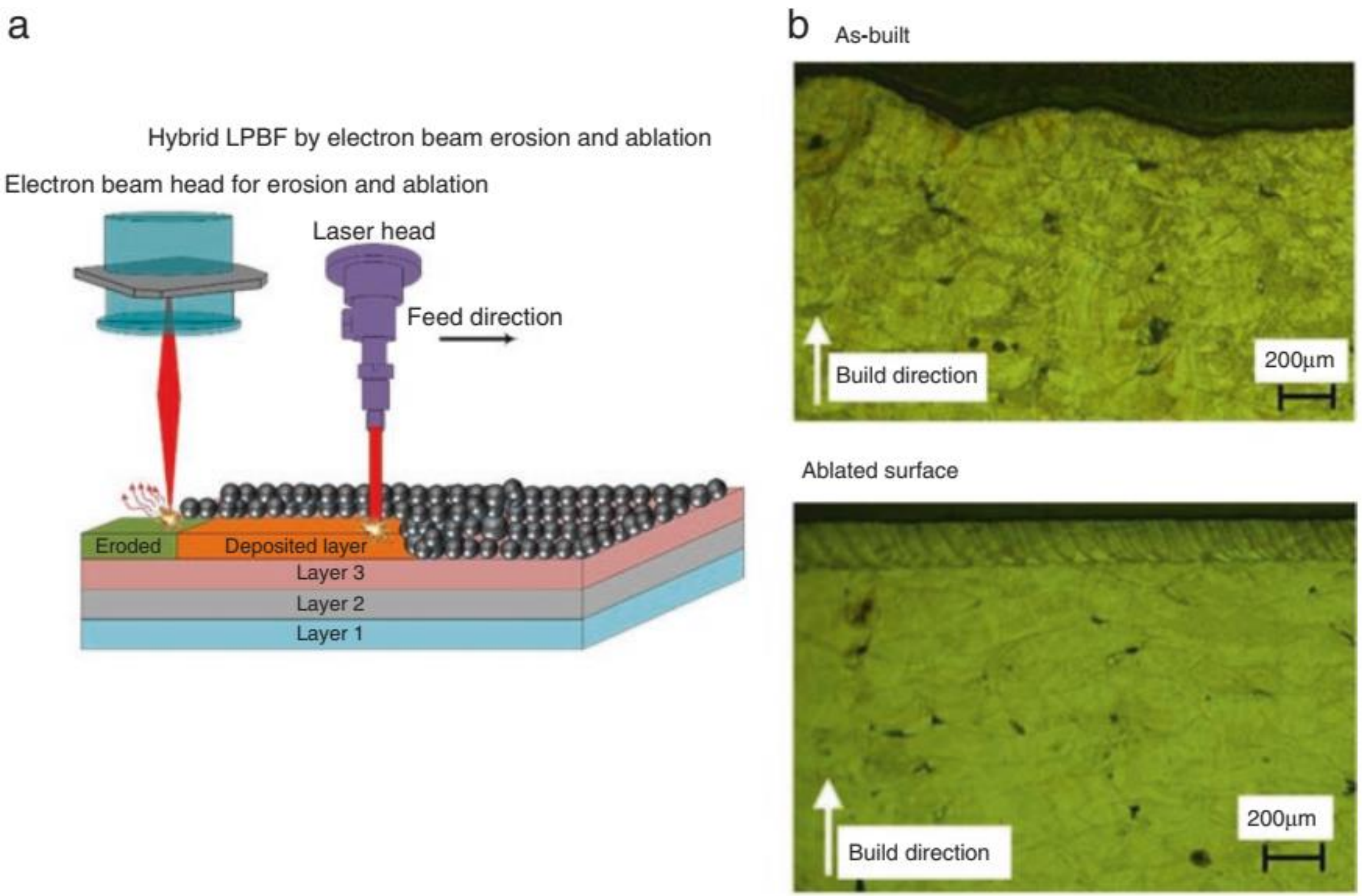


Fig. 12.10 Hybrid LB-PBF by electron beam erosion and ablation (**b**) SEM image of as-built and ablated material (Elsevier license number 4630720259893) [38]

- ❑ Ablation and erosion by electron beam increases the **thermal residual stress**, which can be a problem in materials with low thermal conductivity (such as Ti alloys)

Sequential Hybrid AM Classification: Peening (*shot*)

- In shot peening, beads with high kinetic energy induce **plastic deformation** and increase **work hardening** when they bounce off the surface of an object.
- Shot peening improves **microstructure**, **mechanical properties**, and **surface quality**.
- Bead material and hardness (**metal**, **ceramic**, or **glass**): depend on the properties of the printed object.

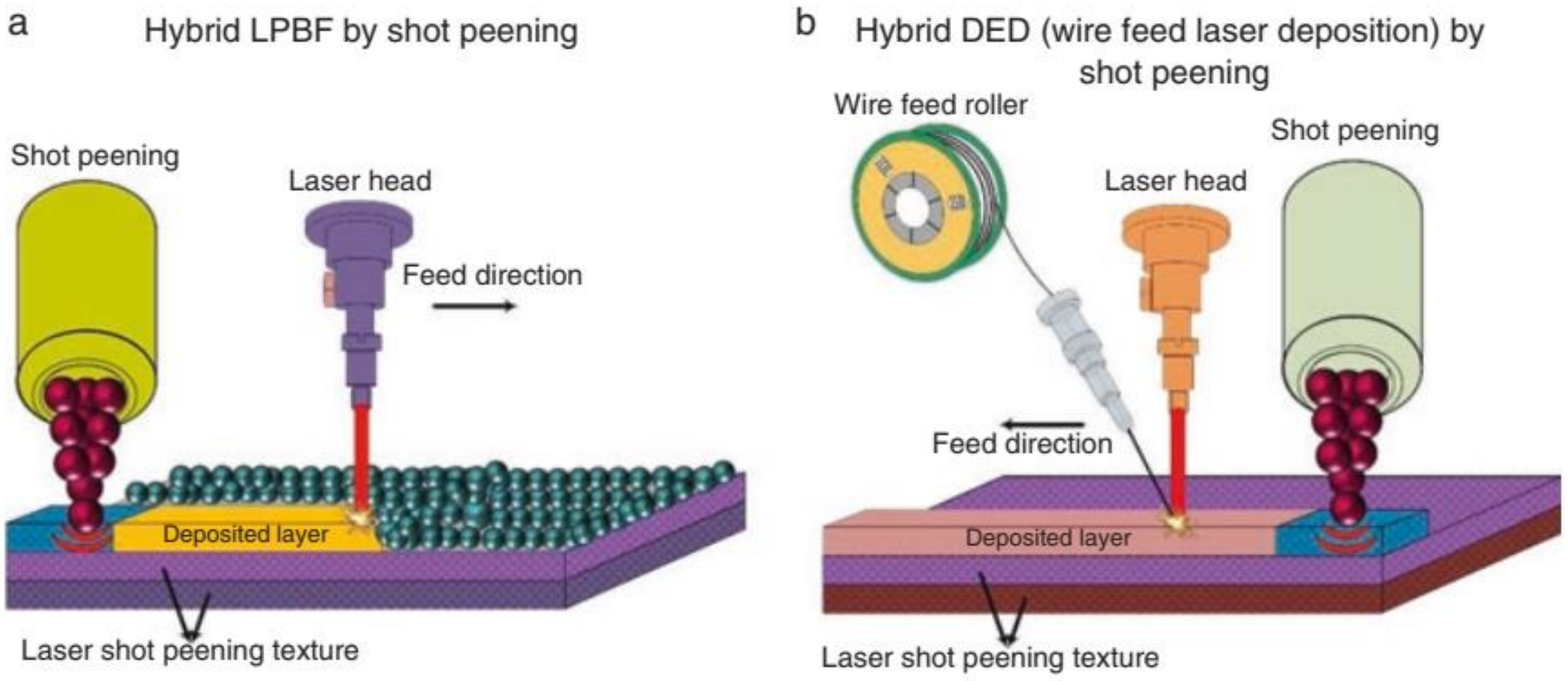
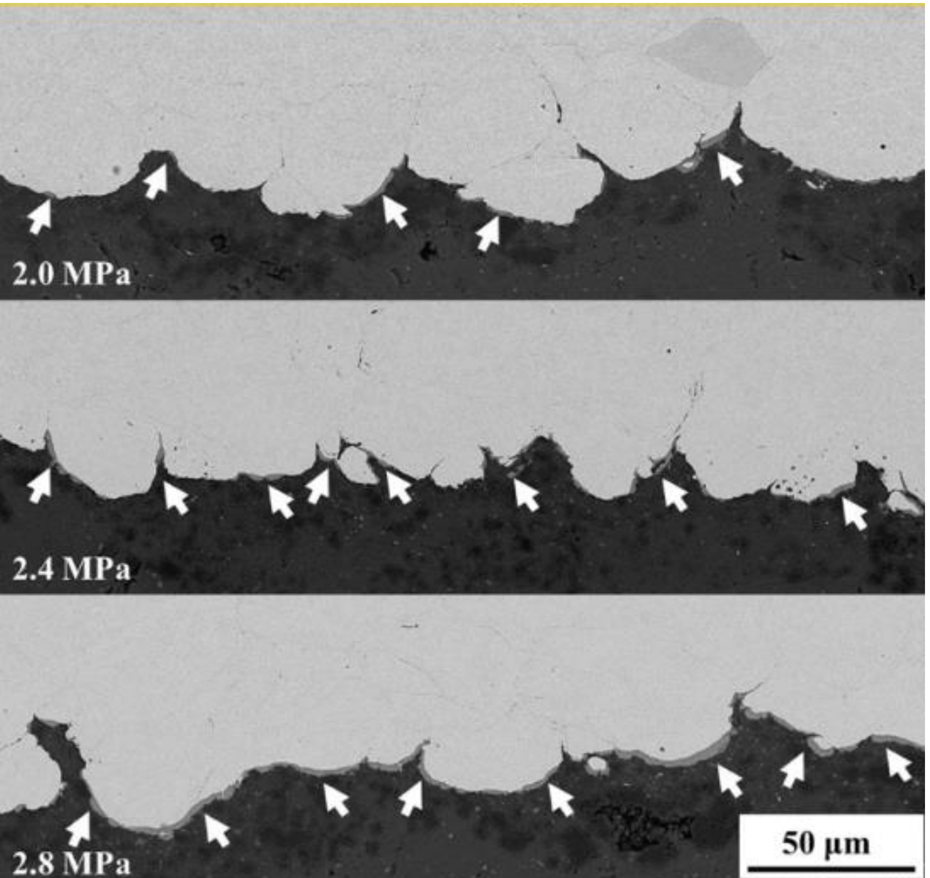


Fig. 12.11 Hybrid LB-PBF and DED by shot peening

Sequential Hybrid AM Classification: Peening (*shot*)

- Shot peening is an excellent secondary process for **DED**, **MEX**, **cold spray**, and **SHL** AM methods.
- In cold spray AM, shot peening is beneficial for the formation of **metallurgical bonding (**improves bonding and reduces the porosity).



- When using shot peening with **powder AM processes**, to avoid powder **contamination**, an alternative option is to use the **same powder for peening** as is used in the AM process:
  - **has a lower penetration depth**.
  - not a proper choice for **soft** materials such as **polymers** (high risk of **bead deformation**).
  - Deformed beads produce rougher surfaces (may need **post-processing** which further adds to the **cost**).

Interfacial bonding features of Ni coating with different propelling gas pressures after heat treatment with diffusion layer marked by arrows

Sequential Hybrid AM Classification: Peening (*Ultrasonic*)

- Hybrid AM by ultrasonic peening is a **low-cost** and **rapid** process compared with many other methods.
- Enhances **surface quality**, **fatigue** resistance, **corrosion** resistance, **tribological performance**, and **microstructure (columnar grain refinement** and **relieving induced residual stresses**).

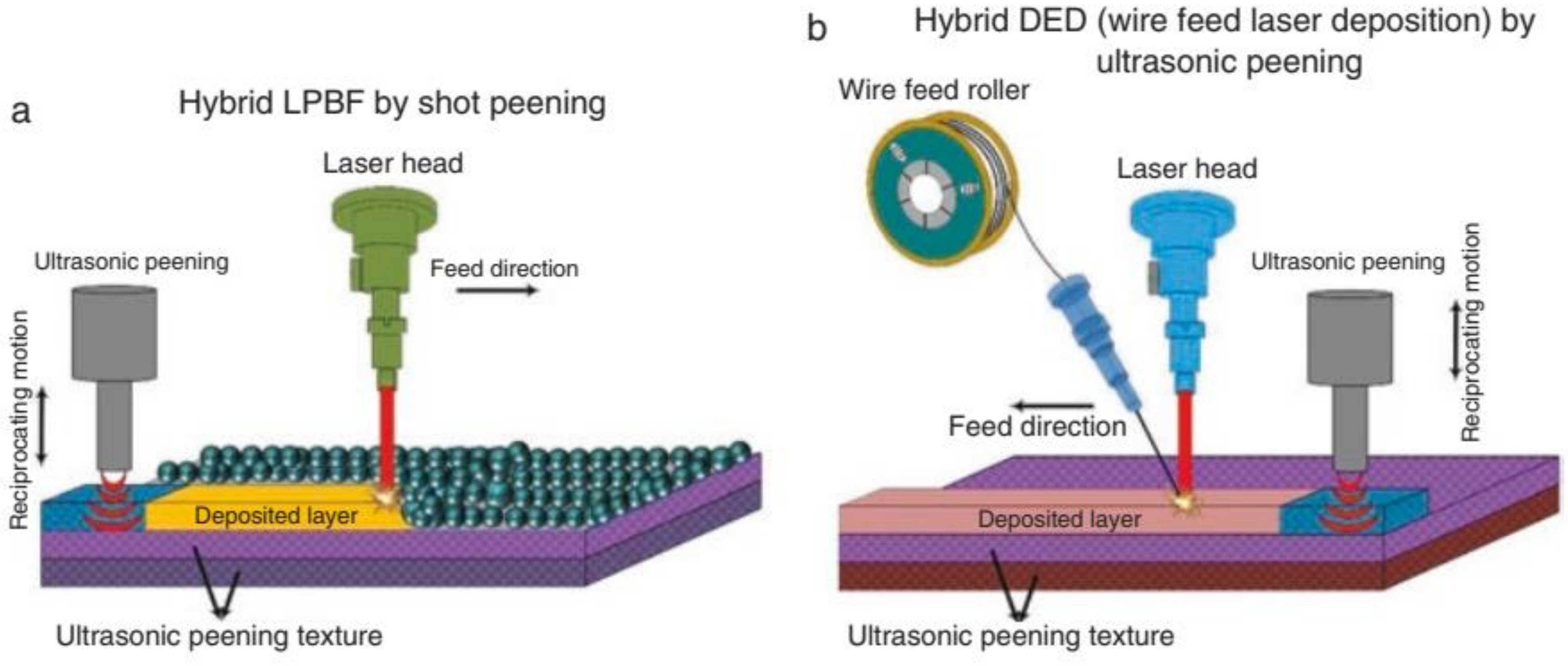


Fig. 12.12 Hybrid LB-PBF and DED by ultrasonic peening

Sequential Hybrid AM Classification: Peening (*Laser shock*)

- Shock waves are produced **by recoil pressure** generated by plasma formed from **laser-material interactions**.
- The shock can be **amplified** through the use of **one** or **two overlays (**like **water)**.
- Advantage (over other peening methods): **deeper** compressive residual stresses are developed.
- By **changing how often laser shock peening** is applied between layers, **functionally graded properties** can be produced.

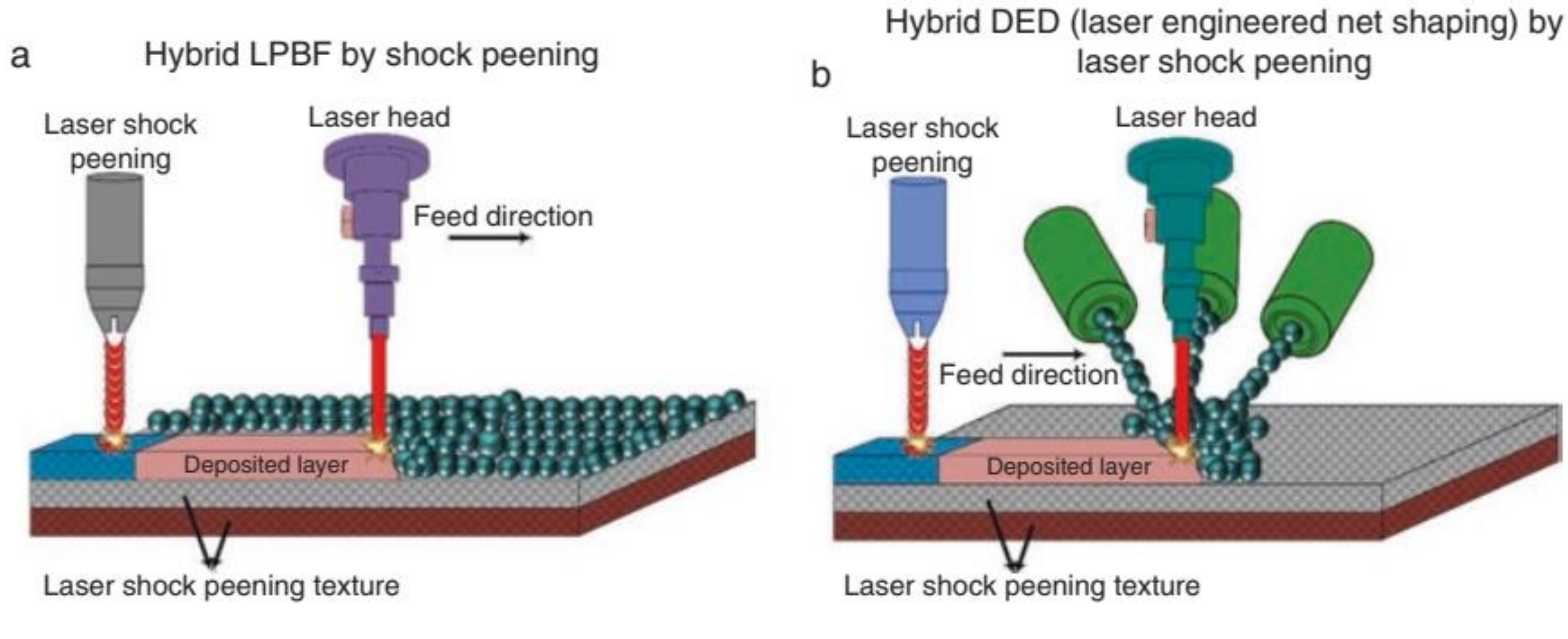
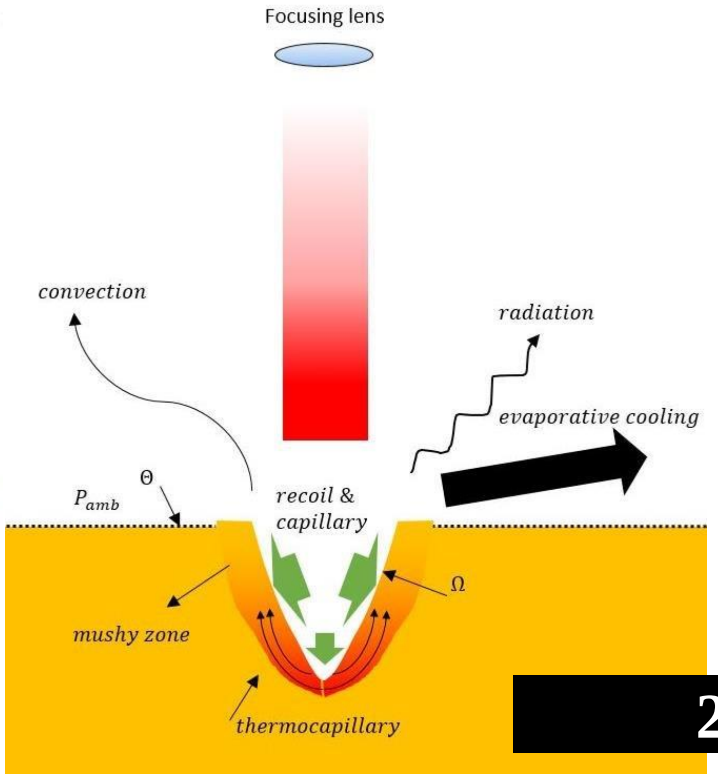
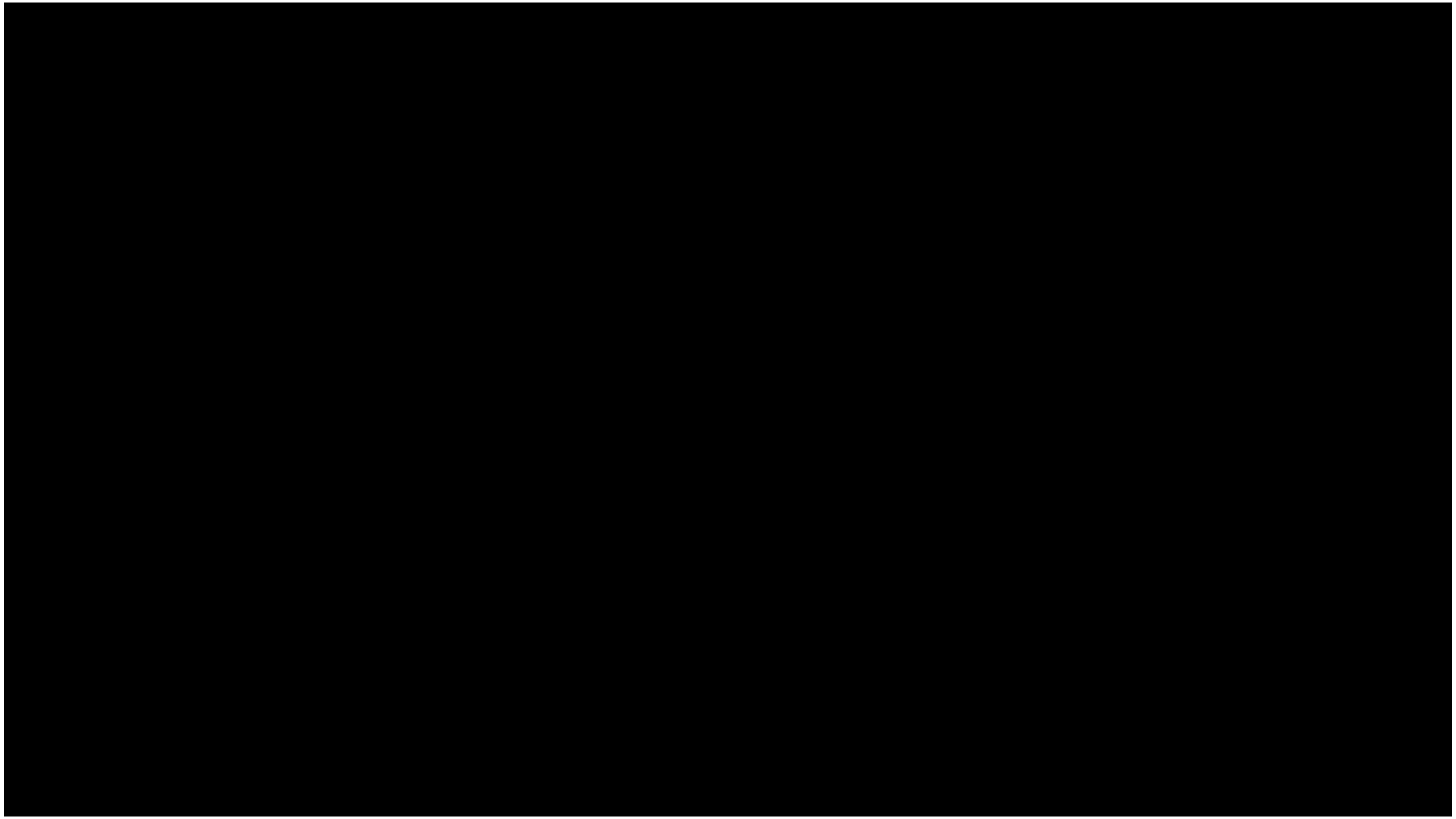


Fig. 12.13 Hybrid LB-PBF and DED by laser shock peening



Sequential Hybrid AM Classification: Pulsed Laser Deposition

- In pulsed laser deposition, a pulsed laser melts the deposited material, and **laser shock** peens the material.
- The **secondary** process can use the **same energy source** as the **primary** AM process.



Sequential Hybrid AM Classification: Pulsed Laser Deposition

- The deposited layer is **deformed**, and the **microstructure** and **mechanical** properties are **enhanced**.
- The **residual stress** is controlled and reduced.
- Very complex process and needs extensive knowledge of melting, solidification, phase change, and so on.

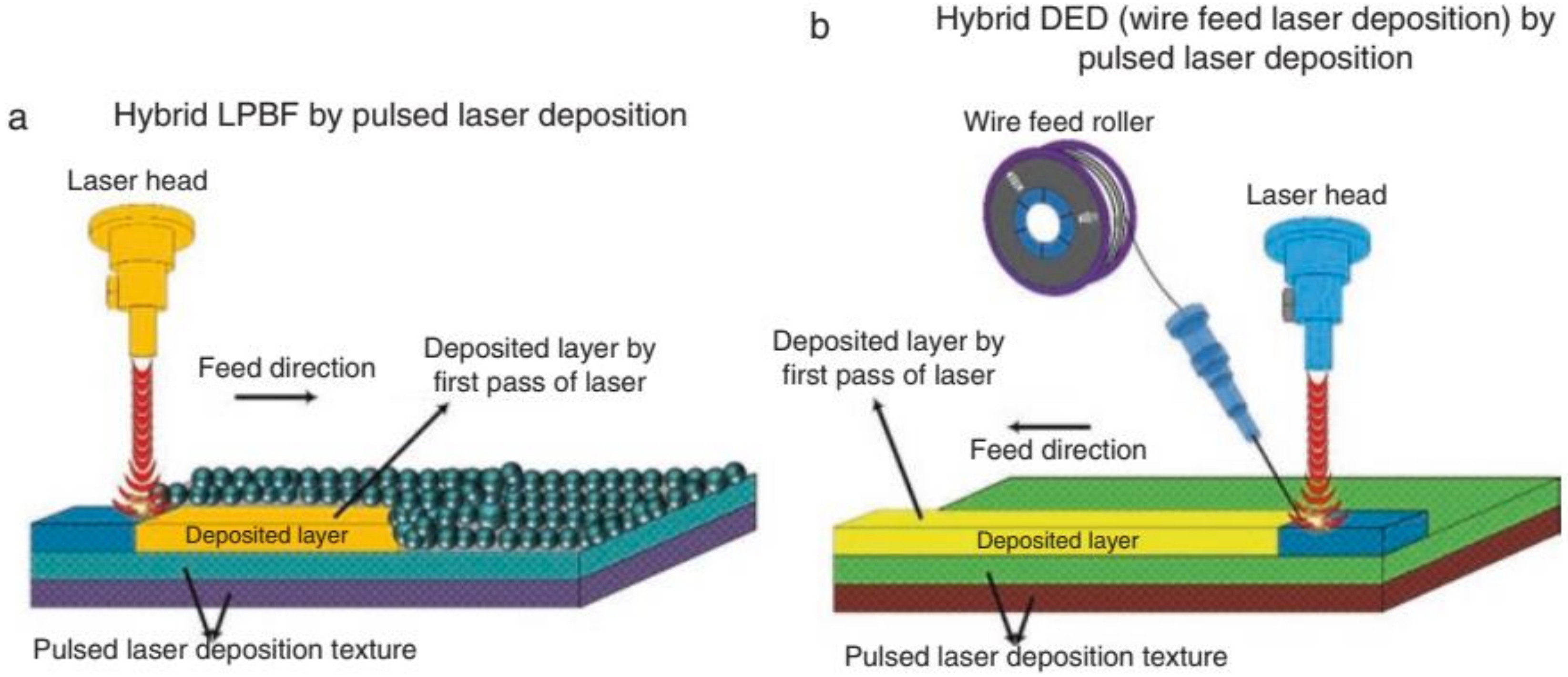


Fig. 12.14 (**a**) Hybrid LB-PBF by pulsed laser deposition and (**b**) Hybrid DED (wire feed laser deposition) by pulsed laser deposition (both processes used a single laser for deposition and secondary processing)

Sequential Hybrid AM Classification: Remelting

- The energy source can be a **laser** or **electron beam**.
- **Key feature**: using **low laser energy**, which prevents any vaporization or generation of plasma.

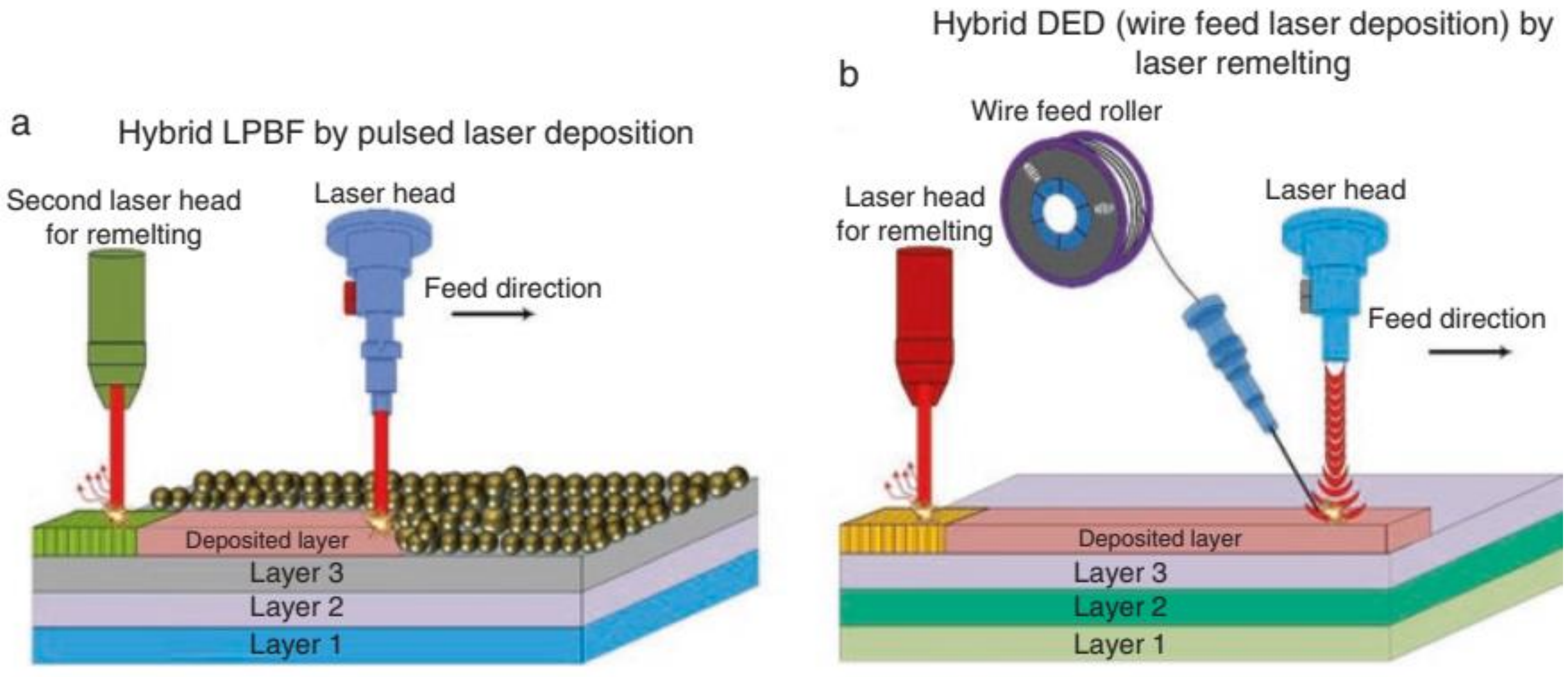


Fig. 12.15 (**a**) Hybrid LB-PBF by laser remelting and (**b**) Hybrid DED by remelting

Sequential Hybrid AM Classification: Remelting

- ❑ Remelting increases the surface temperature to the material's melting point to melt a portion of the surface
- ❑ **Pores, keyholes, and inclusions** are filled during remelting (increased density and part quality).
- ❑ Can improve the **fatigue** and **toughness** properties.

Sequential Hybrid AM Classification: Laser-Assisted Plasma Deposition (PAAM)

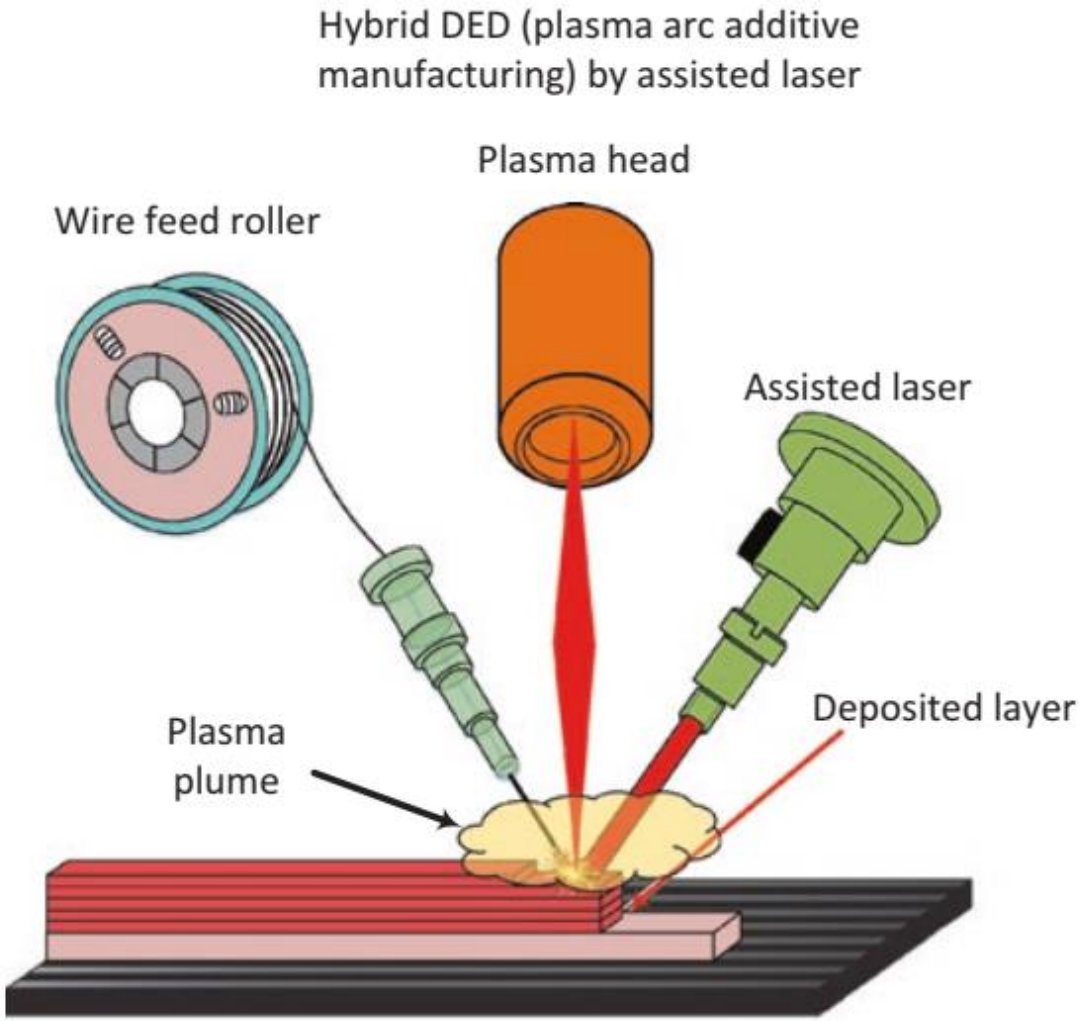


Fig. 12.16 Hybrid PAAM by assisted laser

- In PAAM, due to **high recoil pressure** and **cooling rate**, **rough surfaces** are produced.
- **Laser assistance** as a secondary source of energy can be used simultaneously to improve the surface quality
- The assisted laser provides **extra energy** that helps in the **formation of the plasma** and **improves the deposition** process.
- A **deeper melt pool**, **improved microstructure**, and **decreased porosity**, compared to plasma deposition without the assisting laser.