

A review of laser materials processing paradigms

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Laser-based processing of materials has progressed from traditional applications such as macroscale cutting and welding, to sophisticated techniques, including ultrafast micromachining, additive manufacturing, and surface engineering at micro- and nano-metric scales. Innovations in laser source technology, particularly the advent of high-power and ultrashort-pulse lasers, have expanded the range of processable materials, enabled a plethora of manufacturing applications, and propelled groundbreaking research in optics, photonics, electronics, and biomedical domains. In this article, we provide a concise, yet broad review of the congruent evolution of lasers and materials processing, and highlight seminal developments in the field over the years, combined with a critical assessment of the state of the art. Finally, we also provide an outlook on emerging needs, as well as a roadmap of anticipated developments in laser technologies and materials platforms over the next 50 years.

Overview

Laser materials processing has become an enabling technology in modern manufacturing, making possible the precise, efficient, and flexible processing of a wide range of materials. Since the invention of the laser in 1960, laser technologies and the resulting impact on industry have evolved significantly, expanding from early applications such as cutting and welding of metals to now include waveguide writing, surface patterning, additive manufacturing, and micromachining for a multitude of material classes.^{1–3} This rapid development has been fueled by advances in laser sources, optics, and process control, as well as the growing demand for high-performance, cost-effective, and sustainable manufacturing solutions.

A review of laser materials processing is particularly timely given the significant changes and innovations seen over the past 50 years. The last one to two decades alone have witnessed the rise and industrial adoption of additive manufacturing, where lasers play a central role in fabricating complex

geometries and novel material combinations.⁴ Ultrafast lasers have enabled high-precision processing with minimal heat-affected zones, opening new possibilities in electronics, photonics, and biomedical device fabrication.¹ Additionally, the integration of lasers with digital manufacturing, robotics, and real-time monitoring systems is driving the emergence of smart factories and Industry 4.0 concepts.^{5,6} Beyond manufacturing, it is worth noting that lasers are also driving a renaissance in nuclear fusion research, development, and investments since the 2022 breakthrough in fusion ignition.⁷

The need for a comprehensive review arises from the sheer diversity and complexity of laser-based processes and their applications. Today's engineer seeking a materials processing solution to a complex manufacturing challenge is faced with a myriad of material-dependent options, all with varying price points. Fortunately, along with the last 50 years of laser source and process application development, the understanding of laser–matter interactions has also deepened, supported

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by advances in computational power, modeling and diagnostics,⁸ leading to more reliable processing strategies.

This article aims to provide a concise yet thorough overview of the current state of laser materials processing, tracing its historical development, highlighting several exemplary applications, and discussing recent advances and future challenges. Specifically, in the “[Overview](#)” section, we present a brief history of laser technologies, followed by an overview of laser–matter interactions driving materials processing in the “[Brief history of laser technologies in materials processing](#)” section. The “[Overview of pertinent laser–matter interactions](#)” section then examines the physics, laser technologies, applications, and future challenges in three general areas of laser materials processing: Conventional (e.g., welding and cutting), additive manufacturing, and subtractive/hybrid laser processing. The “[State of the art in laser materials processing](#)” section identifies emerging applications in both, laser technologies and material systems, and presents a forward-looking roadmap for the field over the next 50 years. Ultimately, the goal is to offer researchers and practitioners alike a clear perspective on the current status, process paradigms, and an outlook of this ever-evolving field.

Brief history of laser technologies in materials processing

Lasers have been integral to processing and manufacturing of materials since their invention in 1960. The last 50 years in particular have seen tremendous progress in laser technologies and an evolution toward more efficient, powerful, functional, and compact architectures, as displayed in [Table I](#). One of the earliest lasers used for materials processing was the CO₂ laser, which produces light at a wavelength of 10.6 μm using an electrically excited gaseous medium.⁹ CO₂ lasers have long been preferred for high-power cutting and welding because of their excellent beam quality, high efficiency, and relatively low operating costs.¹⁰ While high-power lasers can suffer from poor beam quality (typically measured by M^2 , which is 1 for a perfect, diffraction-limited Gaussian beam) due to thermal lensing and aberrations, CO₂ lasers typically exhibit close to diffraction-limited beam quality due to the gas medium minimizing thermal lensing and facilitating stability under high-power loads.^{11,12} Today’s CO₂ lasers produce tens of kilowatts (kW) of average power and are used extensively in cutting, marking, and glass processing applications. However, for applications requiring flexible beam delivery through optical fibers, Nd:YAG lasers became the standard due to their shorter wavelength and compatibility with silica fibers.¹³ The first industrial solid-state lasers were lamp-pumped Nd:YAG systems. Later, these lamps were replaced by diode pumping, which greatly improved both efficiency and system robustness.¹⁴ Modern diode-pumped lasers can now achieve lifespans of up to 20,000 operating hours and output several kilowatts of average power, making them suitable for demanding industrial environments.¹⁵ This transition also enabled more compact, energy-efficient, and

maintenance-friendly laser systems.¹⁶ Disk lasers—another variant of solid-state architectures—involve lasing within a thin-disk-shaped Yb:YAG crystal (generally), and can produce up to several kilowatts of average power at 1.03- μm wavelengths.¹⁷ For example, a single-disk configuration was employed to achieve single-mode beam quality ($M^2=1.38$) with an average power of 4 kW¹⁸ and multimode ($M^2=10$) quality with average power = 10 kW, while multidisk configurations can go beyond 20 kW.¹⁹ As opposed to conventional rod or slab-based architectures, the unique design of the disk laser (first invented in the early 1990s) improves heat extraction during operation, promotes good beam quality, and makes them suitable for high-power materials processing.²⁰ Excimer lasers—another important class of gas lasers—emit light in the ultraviolet (UV) spectral region and consequently enable high energy and high-resolution laser–material interactions. They use a combination of a noble gas (argon, krypton, or xenon) and a reactive gas, driven by electrical stimulation at high pressure to form a molecule (excimer), which produces pulsed UV laser light at hundreds of watts of average output power. Since the first demonstration of excimer lasing in 1970, these lasers have been integral to industrial applications requiring high precision, such as semiconductor lithography, marking, and micromachining.²¹

Fiber lasers—a specialized type of solid-state laser—have become so widespread that they are often regarded as a distinct category. These systems use diode lasers to efficiently pump a fiber-based active medium, such as ytterbium-doped fiber, typically emitting between 1.03 and 1.08 μm .²² Depending on the fiber dopant, the output wavelength can be tuned over a broader range (1.03–2.1 μm) at powers of tens of kW, allowing for process optimization across different materials.²³ Historically, high-power lasers were limited to two main wavelengths: 10.6 μm (CO₂) and 1.06 μm (Nd:YAG), which restricted process optimization options to adjustments in power, focus, and speed.²⁴ The flexibility and reliability of fiber lasers now allow for maintenance-free operation over tens of thousands of hours while also providing greater compactness and energy efficiency than earlier solid-state designs.²⁵ Fiber lasers are now the dominant technology in many cutting, welding, additive and marking applications, and their adoption continues to grow.^{23–26}

Ultrafast lasers, defined by femtosecond (fs) and picosecond (ps) pulse durations, have become crucial for materials processing over the past 30 years.²⁷ The development of short-pulse laser technology began soon after the invention of the laser, with a Q-switched ruby laser producing ~100 ns pulses in 1962.²⁸ By the 1970s, mode-locked Nd:glass lasers achieved 10 ps pulses,²⁹ and the first fs pulses were generated using mode-locked dye lasers.³⁰ A typical modern Q-switched Nd:YAG laser can deliver ~5 ns pulses with ~1 J energy per pulse at 10 Hz repetition rates.³¹ Similarly, disk laser designs allow for the generation of high-power, pulsed (nano-, pico-, and femtosecond) output as a Q-switched laser or as a laser amplifier.^{20,32} In the 1980s, dye lasers were the primary source

Table I. An overview of lasers employed in materials processing applications and typical technical specifications. Information and data sourced from References 44–51.

Laser Type	Laser Technology	Wavelength (μm)	Pulse Duration	Average Power	Cost per Watt (High-Power Variants)	Market Presence	Applications	Other Notes
Gas	Excimer (ArF, KrF, XeCl)	0.12 – 0.35	10 ns – tens of μs	Hundreds of W	\$1000/W	\$0.59B (2022)	Semiconductor lithography, marking, annealing	CW operation not possible
	CO ₂	9.4 and 10.6	ms – μs	1970s – few kW; 2020s – tens of kW	< \$60/W	\$3.2B (2024)	Cutting, marking, glass processing	Bulky footprint. High-power applications being taken over by fiber lasers.
Solid state	Nd:YAG (diode-pumped); Yb:YAG (disk); Ti:sapphire	1.03 (YAG); 0.65 – 1.1 (Ti:sapphire)	CW – fs pulsed	Several kW (YAG); Up to 3 W (Ti:sapphire)	\$130 – \$180/W (for diode-pumped and disk variants)	\$3.9B (2024)	Glass and metals processing, 2PP, laser machining	High repetition rate (GHz) output possible (Yb architectures)
Fiber	Yb:glass, Nd:glass	1.03 – 1.08	CW – fs; (Q-switching used for ns pulses)	2012 – 1 kW; 2020s – tens of kW	\$10/W for cw variants (2021)	\$4.2B (2024)	Metal AM, welding, cutting, high-power processing	Small footprint, high cooling efficiency, low capital cost
Diode	GaAs, InGaAs or other semiconductors	0.45 – 3.3	CW or pulsed (0.1 ps – 10 ps)	1990s – 1 kW; 2020s – 50 kW	\$130/W (large variability due to range of options)	\$7.2B (2025)	Brazing, hardening, annealing, semiconductor processing, metal AM	Compact architectures, high efficiency (40%)

of ultrafast pulses (10–100 fs), but solid-state lasers overtook them by the mid-1990s.³² Today, advanced solid-state ultrafast lasers can deliver hundreds of watts of average power, with pulses lasting just a few fs, and can operate at high (hundreds of kilohertz up to gigahertz) repetition rates, enabling new applications in high-resolution micro-/nanomachining, scalable two-photon three-dimensional (3D) printing, photonics (waveguide writing in glass, metasurface fabrication, printing of fiber Bragg gratings), surface functionalization (for inducing hydrophobicity and friction reduction), energy/battery technology (electrode texturing, selective coating removal), and laser surgery, at much faster processing speeds.^{33–35} In another notable development, the first successful laboratory-scale operation of the Ti:sapphire laser in 1982 laid the foundation for subsequent advances in the field, leveraging the broad tunability (650 nm–1100 nm) and the possibility of generating high-intensity, sub-100 fs pulses in advanced architectures. These developments positioned their status as the backbone of ultrafast and high-intensity science in the coming decades.

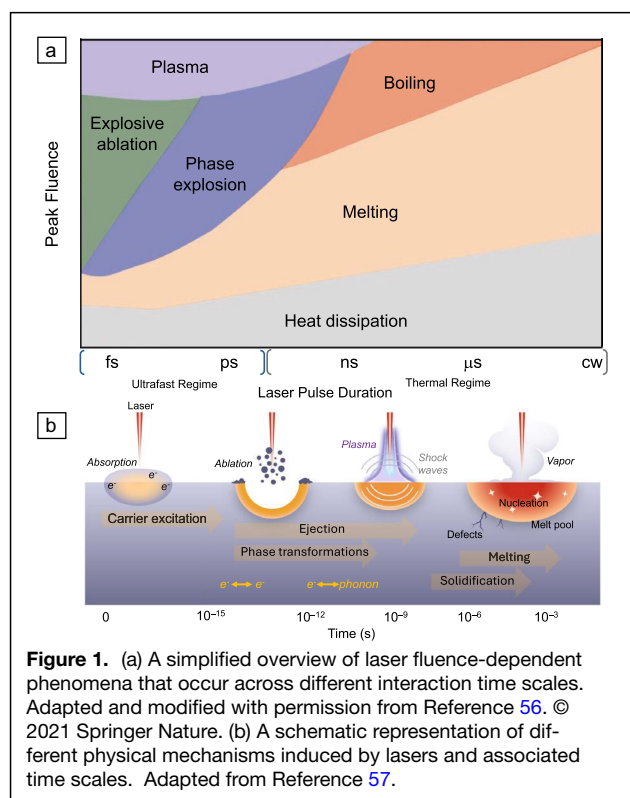
By the late 1980s, high-power semiconductor (diode) lasers had become commercially available,³⁶ enabling the development of diode-pumped solid-state lasers.¹⁴ This was soon followed by the introduction of centimeter-length diode bars mounted on high-performance heatsinks. Using a rack and stack packaging technology then enabled the average power operation of extended two-dimensional (2D) arrays.³⁷ Leveraging the high spatial radiance of diode emitters in their fast-axis dimension, researchers then developed microlens arrays that enabled efficient collimation and focusing of large 2D arrays in their fast-axis dimension.³⁸ As a result, large multi-kilowatt diode arrays can now be focused to irradiances approaching 100 kW/cm², making direct-diode material processing applications such as cutting, welding, and surface hardening possible.³⁹ Today, diode lasers are widely used for metal joining (e.g., brazing), surface hardening, steel coating,

metal additive manufacturing, and semiconductor manufacturing.^{40,41} They are among the most efficient lasers for converting electrical energy into optical output, achieving wall-plug efficiencies of up to 45–60 percent.

Reflecting these technological advances, the entire laser materials processing market has grown rapidly—from about USD\$573 million in 1999 to an estimated USD\$7.2 billion in 2025 globally, representing a compound annual growth rate of 8.5 percent.^{42,43} Today's lasers offer high fluences, coherent control and the ability to dynamically modulate the output beam—a far cry from the passive, low-efficiency architectures of the past. **Table I** provides a technoeconomic overview of laser architectures that are typically employed in current materials processing applications. Laser systems in the coming decades will be intelligent and adaptive, delivering higher powers in smaller architectures, enabling faster dynamic tunability, and providing better functionality in terms of materials processing, as will be discussed in this article.

Overview of pertinent laser–matter interactions

The interaction between laser radiation and a material depends on the parameters of the laser beam (continuous or pulsed, pulse length, wavelength, irradiation energy density, polarization, temporal and spatial coherence), process conditions (such as the dwell time and angle of incidence of the beam), as well as the physicochemical properties, structure and characteristic length scales of the irradiated target.⁵² In the most straightforward description that may be applied to the conventional laser processing of materials with pulses longer than nanoseconds (ns), or in the continuous-wave (cw) regime, the photons interact with the electrons and then energy is transferred to the lattice via collisions in the case of metals, or couple to phonons in the case of insulators. In either case, the excitation of energy carriers happens at time scales much shorter than the laser pulse length and



consequently a thermal description of the material response can be adopted. As the laser beam intensity or pulse energy density (fluence) increases, melting phase transformation may occur (**Figure 1**). At higher laser irradiation, vapor is ejected and may in turn be ionized after interacting with the still-impinging laser beam that then couples with the irradiated target through the plasma. Depending on the background gas composition and pressure, these phenomena can be accompanied by shock wave transmission into the ambient medium. The ejected plume exerts a recoil pressure on the molten phase triggering fluidic instabilities that in addition to thermocapillary events, lead to the release of material in the form of droplets of various sizes and liquid column streaks (**Figure 1b**). The above sequence is generally observed in metal machining processes. Materials with relatively long thermalization times (such as polymers), can undergo photochemical ablation with short-wavelength ns lasers, producing well-defined ablation regions with small heat-affected zones.⁵³ Laser processing of certain semiconductors, insulators and graphite-like materials could proceed via spallation and fragmentation rather than melt-mediated material removal.⁵⁴

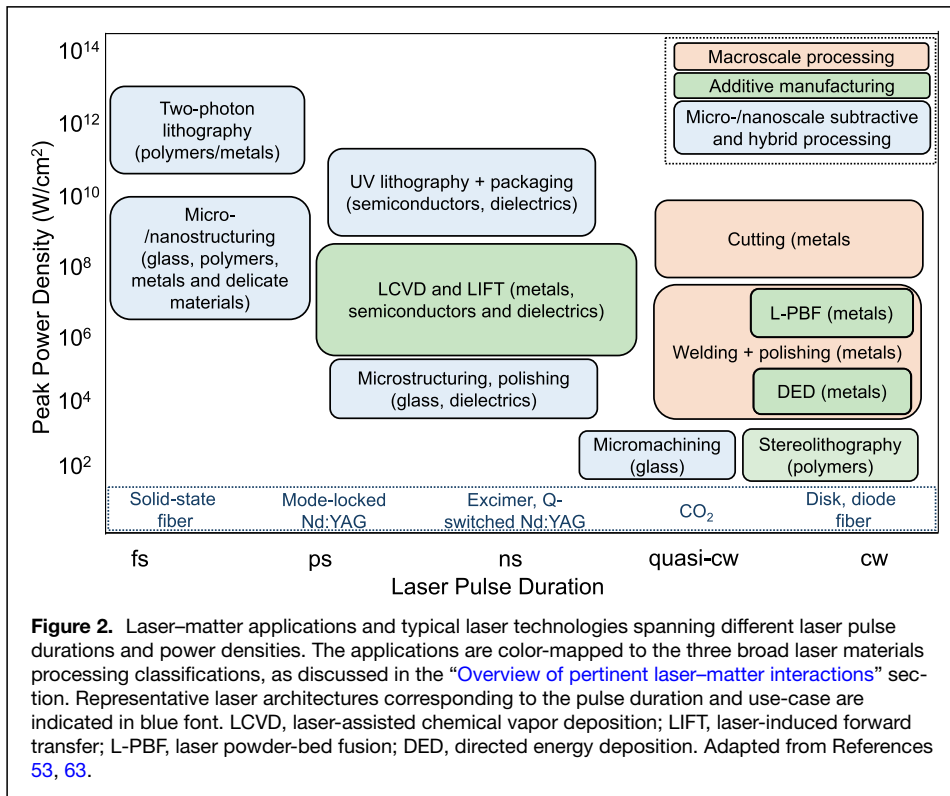
As laser light can be focused to small domains (e.g., micrometer scale with tight focusing far-field optics) and can impart heating at very fast rates (as fast as 10^{15} K/s), laser thermophysical and thermochemical interactions with materials are distinct from typical thermal processing by heat sources (such as infrared lamps, heaters, or blanket furnace heating).

On the other hand, the extremely fast quenching rates (exceeding 10^{13} K/s in ultrafast laser processing of metals) can be used to synthesize materials with novel micro-/nanostructures.⁵⁵ At high photon energies, excited photocarriers can also initiate nonthermal photochemical interactions with no appreciable change of the specimen temperature. It is possible that photophysical processes involve both thermal and photochemical components whose relative contributions depend on the yield of the relative reaction channels. In ns laser ablation, because of single-photon or multiphoton excitation, ablation may occur through direct bond-breaking that can potentially be accompanied by temperature rise. Defects may be generated either due to induced stresses or bond-breaking, leading to volumetric changes and stress buildup culminating in material disintegration and ablative expulsion.

Compared to ns to cw lasers, ultrafast lasers offer a fundamentally different material processing paradigm, as the events happening in the extremely short-pulse duration dictate the ensuing process trajectory (**Figure 1**).⁵⁸ The induced strong electronic, thermal, and mechanical nonequilibrium triggers phase transformations at conditions of strong overheating/undercooling as well as generation of crystal defects.⁵⁵ Upon fs laser irradiation, electrons attain temperatures of thousands of degrees Kelvin and diffuse rapidly into the irradiated target. Collisional energy transfer to the lattice then raises the lattice temperature typically within several or tens of ps. Destruction of the crystalline structure has been observed before the time needed for thermalization, in a short-lived, athermal, ultrafast melting process.⁵⁹ If the laser pulse energy is sufficiently high, it can support thermal transition to the liquid phase. The ensuing material expansion launches a rarefaction wave that causes spallation and liquid film disintegration at near-threshold pulse energies. At slightly higher pulse energies, simulations have predicted the so-called explosive ablation mechanisms.^{60,61} As the laser pulse energy increases, plasma is developed over the surface because of collisional processes. The plasma formation is thus decoupled from the much earlier ultrafast energy deposition on the target material. Ultrafast laser interaction with dielectric materials occurs through complex mechanisms as the refractive index may become intensity-dependent due to the abundance of generated electrons by multiphoton ionization, free carrier absorption and avalanche ionization.⁶² The absorbed energy can be converted into electrons and holes that relax through carrier–lattice interaction channels. Self-trapped excitons have sufficient energy (a few electron volts) to cause lattice rearrangement, intrinsic defect accumulation, and damage.

State of the art in laser materials processing

In this section, we provide a synopsis of the state of the art in three main classifications of laser materials processing—macroscale processing, additive manufacturing, and micro-/nanoscale subtractive and hybrid processing. In each case, we highlight laser technologies, pertinent classes of materials, and



the physics driving the application. **Figure 2** provides a complementary overview of the technical discussion presented in this section.

Conventional macroscale processing

Laser macroprocessing can loosely be defined as the machining of parts with dimensions that are visible to the naked eye, with laser-generated features typically larger than a few hundred micrometers. The invention of the laser immediately drew interest from macroscale processing applications, although early adoption was limited to research environments, military applications, and specialized requirements in welding and drilling.^{64,65} Today, the field has witnessed massive adoption at an industrial scale and has continued to evolve rapidly. Many application areas, including laser-based machining (cutting, drilling, scribing, and marking), welding, joining, surface treatment, and structuring have been integral to the growing demands of advanced manufacturing. We will highlight laser cutting and welding as exemplary processes for discussion.

Physics and laser technologies

Laser cutting and welding are guided by various types of laser-matter interaction mechanisms, largely depending on the laser wavelength, pulse duration, material, and the spatial scale of the process. In conventional macroscale applications, a significant amount of research has been performed in the cw

and short (ns) pulse regimes. For metals in this regime, the absorbed laser energy is transferred to electrons (at fs time scales), followed by a transfer to the lattice through electron-phonon coupling (ps). As the electron-phonon coupling time is much smaller than the incident pulse duration, the governing mechanism in laser cutting is melting, where the molten metal is ejected by an assisting gas jet. In laser welding, melting is followed by solidification and fusion of parts. The wavelength-dependence of such thermal processes can be understood using the Drude model,⁶⁶ which describes the behavior of electrons or photo-excited carriers. In general, the absorption coefficient (α) decreases with increasing wavelengths ($\alpha = 4\pi\kappa/\lambda$,

where κ is the extinction coefficient and λ is the wavelength) for radiation below the plasma frequency (ω_p) of the material.⁶⁷ In addition, decreasing the wavelength from far-IR to visible wavelengths in this regime reduces reflectivity and confines the skin depth to shorter regions beneath the surface. Consequently, the spectral regime driving the process predominantly dictates the choice of laser needed for a particular application.

Laser cutting was developed in 1964 at Bell Laboratories, following the invention of the CO₂ laser, and applied by Western Electric a year later for drilling holes in diamond dies.⁶⁸ The process is typically performed by gas directed at the laser-illuminated zone through a nozzle for blowing away molten material from the cut kerf. Alternatively, in remote cutting, the laser is focused onto the process zone, with a working distance larger than ~300 mm, so gas cannot be supplied through a nozzle that is attached to the laser optics head.² Instead, the material is removed by vaporization of the molten metal from the kerf ground. A single laser pass typically can ablate ~100 μm of material and multiple passes are typically employed to achieve higher cutting depths.^{2,68} By 1974, Nd:YAG laser systems were employed in aircraft engine production plants, and the 1990s saw their application in laser cutting of stents for the medical device industry.⁶⁵ The 2000s started seeing widespread adoption of fiber lasers and disk lasers, which offered higher machining efficiency, smaller form factors and improved beam quality. Today, CO₂ and fiber lasers are extensively used to cut and machine metals, wood, leather,

polymers, and materials that are conventionally difficult to machine, with high-precision (well-defined edges and smooth surfaces) and accuracy. Solid-state Nd:YAG lasers are widely employed for machining thinner metals due to their shorter wavelength (1 μm), which can be absorbed by materials more efficiently than at CO₂ laser wavelengths (where metals exhibit high reflectivity). In addition, pulsed mode Nd:YAG lasers can generate higher beam intensity, produce narrower heat-affected zones, and smaller recast layer in the processing zone, making them better suited for processing thin metals than CO₂ lasers.⁶⁹

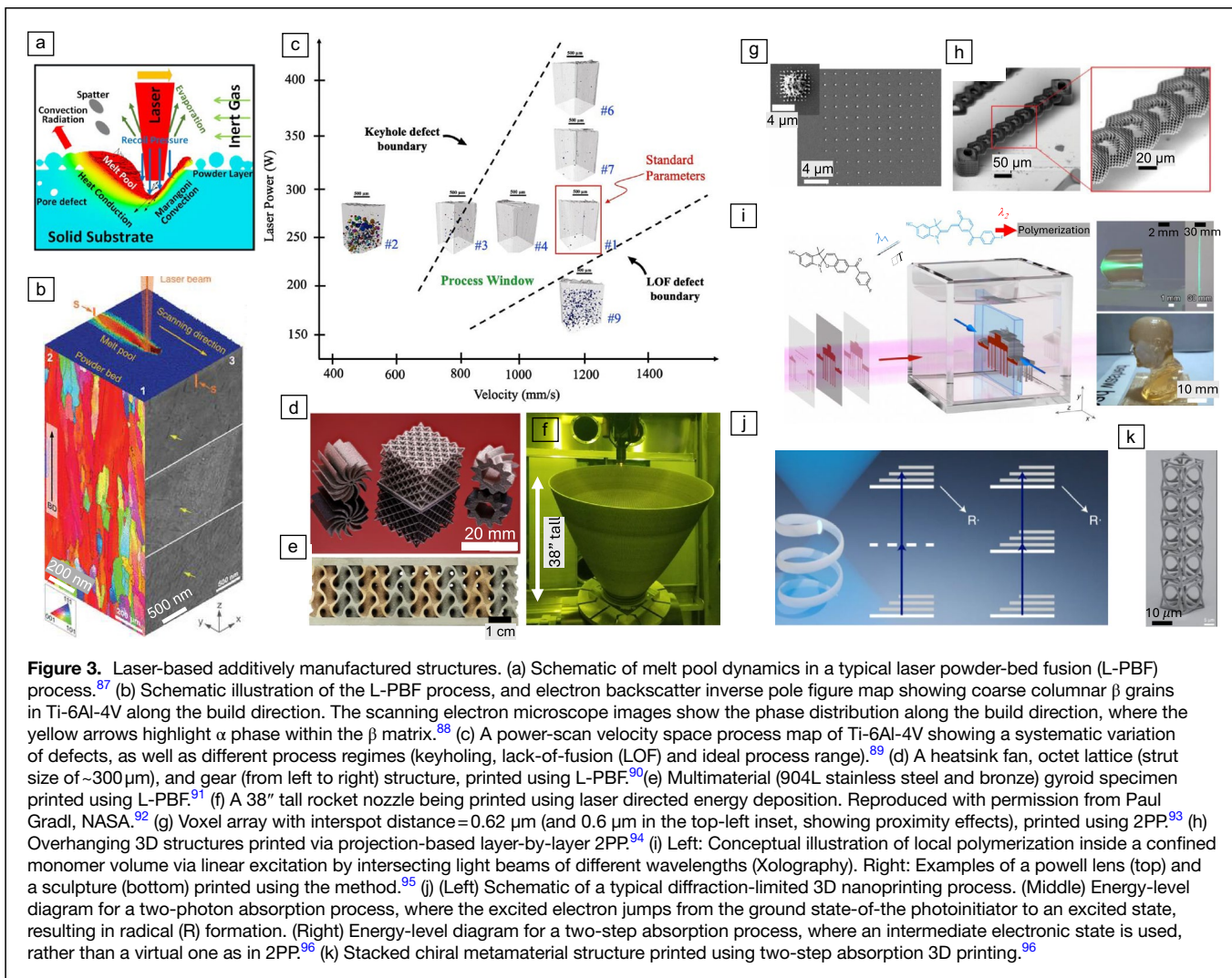
Metal welding was another early adopter of the rapid advances in laser technology (growing congruently with laser cutting). In laser welding, a high-power laser beam is focused and moved along the interface of two stacked materials, which melts and fuses them at the weld seam.² Conduction-mode welding produces melt pools (using power densities $<0.5 \text{ MW/cm}^2$) with shallow, semicircular cross sections. In keyhole-mode welding, higher energy densities ($>1.5 \text{ MW/cm}^2$) are used so that the liquid metal undergoes boiling and expels vaporized material away from the surface and the ejected vapor exerts recoil pressure on the melt pool, creating a deep and narrow keyhole. Penetration-mode welding (or deep penetration welding) typically employs a pulsed laser (such as Nd:YAG) to provide controlled thermal input to generate melt pools with an aspect-ratio (depth/width) of about 1—a regime that is preferred for applications in spot and seam welding.

Applications and key challenges

Evolving improvements in laser technology, beam delivery methods, process control, and monitoring approaches have positioned laser cutting and welding as invaluable processes for automotive, medical device manufacturing, and precision electronics applications. Compared to traditional chemomechanical methods of macroscale processing which tend to use chemicals, slurries, or abrasives, laser-based alternatives offer more versatility and cleanliness for processing a variety of material types due to the noncontact nature of the process. In the automotive sector, numerous metallic and glass components are routinely cut using lasers.⁶⁸ In the context of laser-based processing, the joining of aluminum, steels, and other lightweight materials are predominantly done through laser welding (USD\$2.9 billion market share),^{70,71} but non-laser-based methods such as arc welding have a significantly larger market dominance.⁷² The aerospace industry leverages keyhole-mode welding for processing critical components such as turbine blades and fuel tanks through high-strength joints, but conduction mode is preferred for welding thin gauges due to the need for reduced process instabilities.⁷³ Electronic and medical devices require damage-free and precision processing with minimized heat-affected zones, which cutting and conduction-mode welding enable. Laser welding has also received renewed attention in space applications due to technological advances in high-power, lightweight fiber laser sources and

the fact that components can also be welded in both vacuum and atmospheric pressure without the need for welding electrodes or shielding gas.⁷⁴ These developments have inspired a broader range of macroprocessing applications such as cladding, hardening, and surface texturing.

Despite the growing adoption of macroscale processes over the years, several challenges need to be addressed to meet the demand for processing mechanically robust and lightweight components. In welding, understanding and controlling process artifacts in the melt pool are important to obtain desired microstructures, reduce porosity and pinholes, and produce parts with required joint strengths. Melting and solidification are inevitable in laser-based cutting and welding, which often result in coarse grains and phase changes in the process zone. Rapid heating and cooling cycles induced by welding can lead to solidification cracking in materials such as Hastelloy X and Aluminum 6061, which are critical for aerospace applications.⁶³ These considerations become more important in processing multimaterial joints and dissimilar materials (materials with disparate thermal and optical properties), as secondary phases, intermetallic compounds and brittle phases may form and yield suboptimal joint properties.³ Welding of Cu has critical applications in electromobility, batteries, and electronic applications, but the high reflectivity and high thermal conductivity are detrimental for efficient laser processing. In laser cutting, striations and high surface roughness can manifest due to complex hydrodynamic instabilities and multiple reflections—a problem exacerbated by the use of 1- μm wavelength.² While increasing the laser power can be beneficial in improving process productivity during welding and cutting, laser–vapor and laser–plasma interactions can substantially reduce absorptivity at the process plane and lead to spatter, weld dropout, and other defects in the processed surfaces. Additionally, processing at higher powers can increase the risk of damage to optical systems or the process laser itself, due to back-reflections that occur during processing of materials (particularly for high-reflectivity materials). In an effort to obtain better control over optothermal energy delivery and improve process quality and productivity (beyond what is possible by tuning conventional processing parameters), beam wobbling, beam shaping, and laser pulse width modulation are some strategies that are being explored to obtain better control over the optothermal energy delivery and improve the quality and productivity of laser machining and welding.^{2,63,68} Several types of glasses such as silica, silicates, and phosphates, are important for high-fluence applications. Laser joining enables precise, localized, and scalable assembly of glasses with a high degree of flexibility for processing complex geometries. While CO₂ laser welding is an effective approach for high-volume glass joining due to the high absorptivity (and higher penetration depths) of most glasses at $\sim 10.6 \mu\text{m}$ wavelengths (near the Reststrahlen frequency of the material),^{75,76} the requirement of post-heating steps slows down the process workflow.⁷⁷ Short and ultrashort-pulsed laser glass welding offer a promising alternative, as the welding zone can be minimized by leveraging the nonlinear



nature of absorption (e.g., through multiphoton ionization) to induce high peak intensities in small focal volumes, leading to a smaller thermal diffusion region. While this approach also results in smaller melt volume per time compared to CO_2 laser welding, it offers higher precision and mitigates the need for post-heating.^{77,78}

Additive manufacturing

Additive manufacturing (AM) generally refers to 3D printing using digital designs and a deposition process by which parts are built layer-by-layer. The field has witnessed massive and transformative growth since it was first conceptualized and commercialized in the 1980s, although the first attempt at creating solid objects using a laser was in the late 1960s.⁷⁹ Current AM technologies span metals, polymers, glasses, and composite materials across multiple spatial scales, and its appeal over conventional manufacturing approaches lies in the ability to produce complex structures with reduced waste, improved productivity, and manufacturing flexibility.

Physics and laser technologies

Laser-based AM processes can broadly be classified under distinct physical process categories—selective laser sintering (SLS) and melting (SLM), directed energy deposition (DED) and photopolymerization. In SLS, CO_2 lasers (with average powers ranging from tens to hundreds of watts) are employed to print polymers and ceramics by sintering powder particles at temperatures close to the melting point, as they have high absorptivity at the $10.6\text{-}\mu\text{m}$ wavelength. Yb-fiber and Nd:YAG lasers (with wavelength $\sim 1.06\mu\text{m}$ and powers up to a kilowatt) are commonly employed for sintering ceramics and melt processing of metals. Processing metals is most commonly carried out using SLM (also known as laser powder-bed fusion, L-PBF)—where a scanning laser beam irradiates a bed of metallic powder feedstock to sequentially melt and resolidify structures of the desired shape (Figure 3a–e). The high energy densities employed in the process yield cooling rates in the range of $10^5\text{--}10^7\text{ K/s}$ (about four orders of magnitude higher than in casting), which results in nonequilibrium microstructures with highly textured and oriented columnar

grains. Analogous to laser welding, the melt pool dynamics are governed by steep thermal gradient-induced Marangoni convection, phase transformations, vaporization, and recoil pressure^{80,81} (Figure 3a–b). Another flavor of metal AM involves the feeding of metal powder or wire into a laser-induced melt pool, known as DED or laser metal deposition (Figure 3f).⁸¹ In powder-based DED, feedstock material is delivered through a carrier gas and injected to the melt pool induced by a focused laser beam. Owing to the reliability and speed of feedstock delivery, DED is favored for large-scale components of limited complexity and the processing of functionally graded materials, while L-PBF enables smaller features (tens of microns), complex geometries, and near-net-shape components typically of a single material.⁸²

Stereolithography (SLA) is the most prevalent approach to achieve photopolymerization. The process works using laser light with an appropriate wavelength (typically UV light) to induce absorption, followed by curing and solidification in a vat of suitable liquid resin photopolymer. SLA produces resolutions down to $\sim 100\ \mu\text{m}$, but high-resolution 3D printing strategies such as two-photon polymerization (2PP) of photosensitive materials can produce small ($\sim 100\ \text{nm}$) structures below the diffraction limit of light, through additive or subtractive manufacturing (by the use of either positive- or negative-tone photoresist), Figure 3g–h.^{1,27} Two-photon polymerization relies on a direct writing strategy for inducing two-photon absorption—a nonlinear absorption process where two photons are simultaneously absorbed unlike conventional photopolymerization approaches that use UV or visible radiation to drive the absorption of a single photon. Consequently, the absorption scales as the square of the intensity of light and polymerization significantly occurs where the intensity is the highest. The resolution of the process is primarily dictated by the volume of the laser spot at the beam focus.^{83,84} In addition to photopolymerization, photoreduction of metal ion precursors dissolved in-volume can be performed in hydrogels as well as photoresist solutions,⁸⁵ and the neutralization of metal ions can form a metallic voxel and 3D-print a structure.

Ultrafast lasers (e.g., Yb-fiber or Ti:sapphire) operating in the near-IR wavelengths typically provide necessary energy densities to induce nonlinear absorption and photopolymerization. The choice of photoresist, photoinitiators, and cross-linking agents are crucial in determining the mechanical properties of the polymerized structures as well as their response to temperature variations or residual stresses.⁸⁶ The laser power density and exposure time are critical parameters for producing smooth and continuous features without heat buildup and consequent bubbling, which can result from evaporation of gases.

Applications and key challenges

AM adoption has rapidly risen beyond prototyping and academic use cases over the years. Today, AM is being recognized as a viable solution for several application domains, including lightweighting aerospace components, medical devices,

automotive components, tooling and end-use part production. The choice of laser scan parameters (such as power, scan speed, beam diameter, hatch spacing, hatching strategy, and beam shape) largely determines the process outcome in laser scanning-based AM approaches. Alloy design, laser beam shaping, *in situ* heating, and the addition of nanoparticle inoculants are some strategies that have been successful in optimizing solidification and recrystallization conditions to tune microstructure during L-PBF.^{97–104} Providing insufficient energy density (e.g., by scanning the laser too fast) will result in lack-of-fusion defects and applying too much energy will result in keyhole formation and induce instabilities, spatter, and porosity, which also deteriorate the mechanical properties of the build^{81,105} (Figure 3c). Given the narrow effective processing windows, process control (in combination with in-process sensor diagnostics for acquiring real-time feedback^{106,107}) in L-PBF is key to ensuring part quality, process robustness, and productivity. Frameworks such as tool pathing,¹⁰⁸ real-time laser power feedback (reactive approach),¹⁰⁹ feedforward control (anticipating and compensating for melt pool changes in advance) methods^{110,111} have readily been developed and can be used in commercial L-PBF equipment. L-PBF yields lower build rates ($\sim 90\ \text{cm}^3/\text{h}$) compared to other metal AM methods that do not employ lasers as the energy source, and a significant ongoing challenge is to boost process productivity.⁸⁰ While multi-laser approaches,¹⁰⁴ laser-based lithographic printing,¹¹² and beam shaping¹⁰² have shown promise, only modest ($\sim 2\times$) productivity improvements have been reported and the effect is tied to the optical and thermal properties of the material in consideration. AM, and in particular, laser (blown powder) DED, has been utilized for printing (with build rates on the order of $50\text{--}700\ \text{cm}^3/\text{h}$) and post-processing of components for liquid rocket engines such as nozzles (Figure 3f), injectors, ignition systems combustion chambers, and turbomachinery.^{92,113,114}

Current limitations of 2PP are long print times, poor scalability, and low throughput. Fabrication throughput in 2PP is on the order of $\sim 10^8$ voxels/s, for voxel sizes of $0.1\text{--}1\ \mu\text{m}$. Efforts to improve throughput through parallelization present a tradeoff with the minimum achievable feature size due to a proximity effect, where diffusion artifacts occur during simultaneous writing of structures in close proximity⁹³ (Figure 3g). Several works have sought to increase the speed and versatility of 2PP using advanced laser-based techniques such as multibeam scanning,¹¹⁵ spatiotemporal projection^{94,116} (Figure 3h), and Xolography⁹⁵ (a multiwavelength light sheet approach built on the concept of dual-color polymerization,¹¹⁷ Figure 3i). Chemical additions (cross-linking agents and photosensitizers) are also often made to increase the degree of cross-linking.⁸⁶ Two-step absorption 3D nanoprinting is a low-cost alternative to 2PP, as the process is driven by a cw laser diode that is significantly less expensive and less bulky compared to fs lasers which are commonly used for 2PP. The technique relies on the implementation of a photoinitiator that facilitates two single-photon absorption events, rather than one multiphoton absorption (as in the case of 2PP),

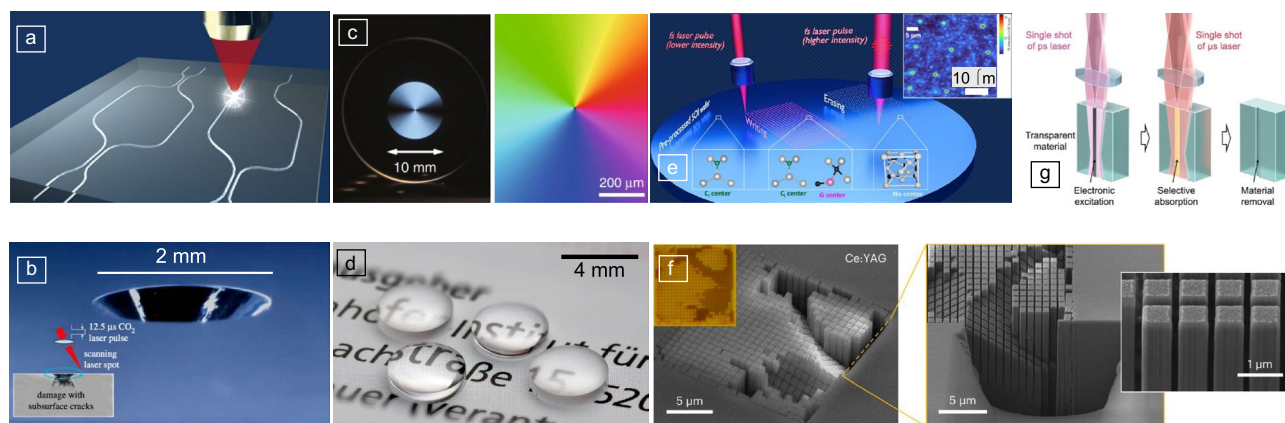


Figure 4. Subtractive laser processing applications. (a) Conceptual illustration of femtosecond (fs) laser microfabrication of optical interferometers in the bulk of a borosilicate slide¹³⁵ (b) Side view optical microscope image of a cone-shaped pit generated (using CO₂ laser micromachining) on fused silica to remove subsurface damage.⁷⁶ Image courtesy: Lawrence Livermore National Laboratory. (c) Geometric phase elements fabricated in silica glass fabricated by ultrafast laser-induced modification for use as a polarization vector beam converter (left). The slow axis phase distribution was varied from 0° to 180° with respect to the azimuth (right).¹⁴³ (d) Lenses manufactured by selective laser-induced etching and subsequent laser polishing (two lenses in the middle). Image courtesy of Fraunhofer ILT. (e) Cartoon representing the approach of using fs irradiation to locally write and erase (at a higher laser fluence) quantum emitters (in the form of G or C₁ centers, which are different combinations of C atom substitutes in the Si lattice) in silicon-on-insulator substrates. The inset shows the photoluminescence spectra of fs-pulse irradiated spots.¹³³ (f) Scanning electron micrographs demonstrating free-form nanodicing of 800-nm rods in a doped Ce:YAG crystal, performed using a fs laser and the concept of “super-stealth dicing.”¹³⁹ (g) Ultrahigh-speed machining of transparent materials using a combination of picosecond (ps) and μs laser pulses to produce filamentation and increased absorption, leading to uniform heating, ablation, and the formation of taperless and crack-free holes inside the transparent material.¹³⁷

enabling nanoscale printing with sub-mW powers (Figure 3j–k). Stimulated emission depletion (STED) is another emerging variation of 2PP, which has improved the resolution of processable features to below 30 nm.¹¹⁸

Other types of laser AM methods have emerged as complementary tools for processing materials beyond polymers and with the goal of improving precision scalability in the sub-micron range. Two-photon reduction (a variant of 2PP) has been leveraged to print metallic structures with in-plane dimensions around 200 nm—a capability that is desirable for electronics, microelectromechanical systems and quantum devices, since current foundry-based microfabrication approaches employ expensive physical masks. With these techniques it is possible to fabricate detailed 3D structures with tailored mechanical¹¹⁹ and optical properties.¹²⁰ Laser-based AM of glasses has been carried out using SLM and DED, but the high viscosity of glass makes processing fine details very challenging.¹²¹ Instead subtractive approaches are more feasible (“**Additive manufacturing**” section). Laser-assisted chemical vapor deposition (LCVD)¹²² facilitates highly localized deposition by exploiting photothermal or photochemical dissociation of gaseous precursors, demonstrating effectiveness for metals, semiconductors, and dielectrics,¹²³ as well as low-dimensional materials.¹²⁴ Laser-induced forward transfer (LIFT) is a specialized micrometer-scale 3D printing technique that uses a pulsed laser to eject and transfer material from a source film to a substrate in close proximity. LIFT exemplifies the adaptability of laser-based manufacturing due to its compatibility with a wide range of donor materials and substrates without the

need for cleanroom equipment. Initially developed for metal printing,¹²⁵ LIFT has found applications in producing high-resolution patterns from semiconductors,¹²⁶ dielectrics,¹²⁷ high entropy alloys (HEAs),¹²⁸ and biological materials.¹²⁹ The key advantages of LIFT include low-cost equipment, fast processing speed, and compatibility with various substrates.

Micro-/nanoscale subtractive and hybrid processing

Subtractive laser processing broadly refers to the removal of material from a surface using a focused laser beam, and hybrid processing entails laser processing methods combined with other laser-based or non-laser-based processing tools. Together, these processes broadly encompass micromachining, micro- and nanoprocessing, ablation, surface polishing, structuring and cleaning, in-volume and 3D processing (**Figure 4**). We will highlight a subset of these applications here.

Physics and laser technologies

Ultrafast lasers are dominantly employed for most subtractive processing applications because their short-pulse widths and high peak energy, as well as the broad choice of output wavelengths, can be leveraged to activate either linear or nonlinear absorption in most materials. Upon absorption, several types of removal mechanisms can occur without significant heat transfer, deeper than the immediate proximity of the irradiated surface (as discussed in the “**Brief history of laser technologies in materials processing**” section). As a result, ultrafast lasers can be applied for processing a diverse range of materials. Laser micro-/nanomachining is typically

accomplished via laser ablation, which can occur through mechanisms such as spallation, phase explosion, phase separation, or fragmentation, depending on the fluence, pulse width, and the type of material.³⁴ In general, fs laser machining produces more precise and smoother edges compared to longer pulses.¹³⁰ Owing to the multiphoton absorption in materials such as silica or sapphire, fs laser pulses are capable of creating defects that induce positive optical refractive index changes at the location of the laser focus, suitable for a one-step formation of optical waveguides (Figure 4a).¹³¹ CO₂ lasers can induce thermomechanical modifications in materials such as glasses, where the absorption at those wavelengths is higher than at lower wavelengths, and are applied for polishing or machining polymers and glasses (Figure 4b). The hybridization of laser processing, initially introduced in the context of laser-assisted machining (LAM)¹³² to increase processing rates, has reached higher fidelity processes such as those used in the semiconductor industry. Single-laser and hybrid approaches enhance the etching rate of brittle and hard materials, enhance the writing speed of structures, and process materials more efficiently (Figure 4f–i). Moreover, they allow for in-volume writing of polymers and metals to fabricate microstructures and induce exotic color centers and nanocrystals in transparent dielectrics for enhanced mechanical and optical properties.

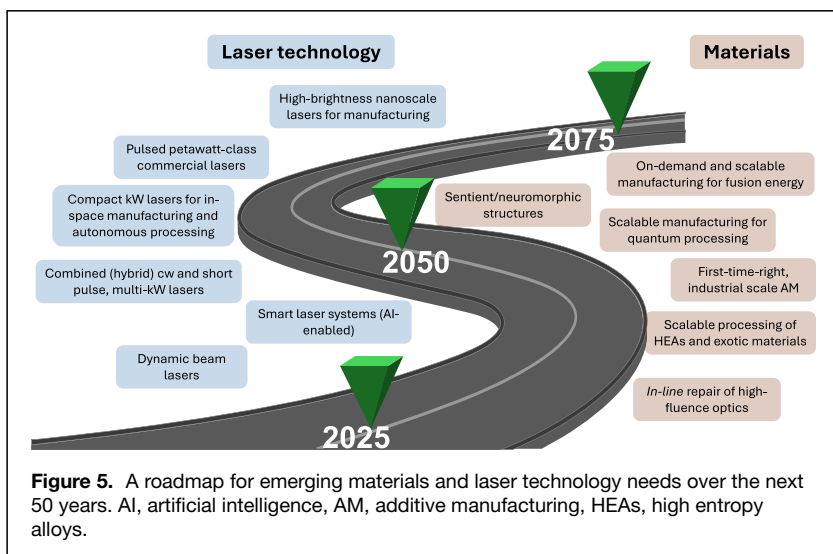
Applications and key challenges

For many years, laser processing of glass has been used in industry for high-volume production (e.g., for cutting, structuring, and the fabrication of 3D optoelectronic devices). Single-laser processes involving CO₂ lasers are routinely used to mitigate surface damage and completely remove laser-induced subsurface damage in optics used in high-fluence applications, such as inertial fusion confinement (ICF) (Figure 4b).⁷⁶ On the other hand, owing to the multiphoton absorption that can occur in certain transparent materials, fs lasers are capable of machining with high precision (Figure 4c). The integration of laser-written waveguides in various material systems offers significant advantages for developing integrated optoelectrical systems. Examples include the formation of light-emitting defects in silicon¹³³ (Figure 4e), waveguide-coupled nitrogen-vacancy centers¹³⁴ and the integration of thermal shifters and waveguides fabricated in glass using a single fs laser.¹³⁵ Aside from inducing permanent refractive index changes, fs lasers offer particular advantages in dielectric processing, including crack-free ablation, minimal debris, and submicron resolution due to the nonlinear absorption mechanism, offering an alternative way for drilling high-aspect-ratio through-glass vias^{136,137} and channeling fluidics,¹³⁸ or debris-free dicing of transparent solids (Figure 4f).¹³⁹ In-volume laser structuring using fs or shorter pulse laser radiation creates complex shaped modifications within glass^{140,141} (Figure 4g), and has been leveraged to produce diffractive optical elements that can change the phase and polarization of incident light^{142,143} (Figure 4c). When combined with an etching process to remove the glass

along the modifications (so-called selective laser-induced etching, SLE), the undesired part is removed (Figure 4d). Since the geometry is written into the volume of the glass, all three surfaces of an optical element (front, back, and edge cylinder) can be manufactured in a single clamping operation, so that they are tolerated on to each other within the limits of machine and process accuracy. Furthermore, aspherical surfaces can be processed at the same cost as spherical surfaces. SLE, as well as direct laser ablation of glass typically lead to rough surfaces of the produced parts. A subsequent laser polishing process can reduce the roughness (*Sa*) from some hundreds of nm down to the sub-nm scale and remove subsurface damage within seconds, by melting a thin surface layer using cw CO₂ laser radiation via adapted tool-paths.^{144–146}

A particular challenge with using a single CO₂ laser is the mitigation of small defects and achieving good surface quality. Instead, single fs laser figuring and polishing has been applied to achieve deterministic material removal with nanometer precision and maintain sub-nm surface roughness in Borofloat 33 glass.¹⁴⁷ Depending on the type of glass, preheating and subsequent annealing may also be necessary to avoid cracking, but as a rule of thumb, materials with a low coefficient of thermal expansion are good candidates for laser polishing. For example, glasses with a high coefficient thermal expansion and low thermal shock resistance (such as borosilicate and boron crown glass) suffer from microcracking due to residual thermomechanical stresses during polishing. Consequently, preheating to 600°C was required to polish them without inducing cracking,¹⁴⁸ whereas fused silica and Pyrex® (with significantly lower coefficients of thermal expansion) are more robust to thermal shock during laser processing.^{148–150} Dual CO₂ or hybrid laser (fs and CO₂) processing has also been utilized for repairing microdefects (<20 µm) and achieving high surface quality (<20 nm) on fused silica.^{151,152} To further enhance shape accuracy, a final high-precision laser ablation process (so-called laser beam figuring) can be used for optical elements made from fused silica: CO₂ lasers with µs pulse duration heat up the surface slightly below the evaporation temperature, resulting in ablation of <5 nm per layer with <100-µm spatial resolution.¹⁵³ This principle is comparable to heating up water to 95°C: although still below the evaporation temperature, the first molecules are already evaporated.

Laser-assisted processing can enable the fabrication of micromechanical devices in glass,¹⁵⁴ accelerate SiC processing,¹⁵⁵ and circumvent the formation of microcracks in Si processing for solar panel production.¹⁵⁶ More exotic techniques treat the laser patterned areas with inductively coupled plasmas to etch, or with ultrasonic baths to strip away the processed areas.¹⁵⁷ Different direct laser writing methods can be combined to reduce the total power needed and increase processing rates. Typically, a single pulse can excite the electrons in a material opening an absorption window for a second pulse to be absorbed.¹⁵⁸ In these schemes, a fs-pulse initiates a plasma with high electron density that can absorb a surrogate ns pulse leading to an increased volume



of the ablation by ~150 percent.¹⁵⁹ With this combination the plasma is located away from the material which reduces heat and cracking effects. In another variant, a vacuum UV laser directly excites the electrons of a ZnO film in the conduction band to absorb a secondary pulse,^{160–162} and the quality of ablated regions was reported to be higher (than when using individual pulses), while the total energy required was reduced by ~5 times.

Emerging needs and outlook for the next 50 years

The next 50 years will continue to see new laser architectures and advanced material systems coevolving and converging to transform and redefine application domains. The following section delves further on how disruptive advances could evolve on both fronts, and **Figure 5** provides a complementary visual roadmap.

Next-generation laser technologies

Innovations in laser technology will play a pivotal role in materials processing in the coming decades, driven by the need for high precision and sustainable manufacturing of a variety of materials with features ranging from sub-nanometric to macroscale. Macroscale processes such as welding, drilling, and cutting benefit from high- and ultrahigh-power lasers ranging from hundreds of watts to greater than 100 kW. However, global energy needs are increasing rapidly and improving wall-plug efficiency and process productivity will be major challenges to tackle in most laser-based processing applications. High-power cw laser sources have become more efficient over the years through continued efforts in improving the design of diode modules and optical gain media, design optimization of fibers, and the integration of optical components in laser modules with lower insertion losses. For instance, wall-plug efficiencies of fiber lasers have grown from ~20% for kW-class

lasers in early 2000s, to >50% for tens of kW turnkey systems in 2025.¹⁶³ The evolution in efficiency, power output, and footprint of other classes of lasers are discussed later in this section. Productivity can be increased by moving toward higher power laser sources to enable faster processing speeds and larger process zones. However, laser–matter interactions get more complex at higher energy inputs and efforts to boost process productivity will require nuanced, application-specific considerations. For example, excessive energy input in processes employing high-power cw lasers (such as welding, cutting, and L-PBF) will lead to more intricate and synergistic laser-melt pool interactions. Larger process zones also reduce feature reso-

lution and increase susceptibility to process artifacts. To this end, process control (as described in the “[Brief history of laser technologies in materials processing](#)” and “[Overview of pertinent laser–matter interactions](#)” sections) will be crucial not just to improve productivity, but also to ensure sufficient part quality and process robustness.

State-of-the-art laser welding and L-PBF machines can already be equipped with features such as adjustable ring (annular)-mode beam shapes,^{164,165} whereas more flexible beam shaping implementations are still in nascent stages for high-power applications.^{101,166} Freeform beam shaping and modulation based on high-power beam shapers (diffractive optical elements, fast galvanometric scanners) enable fast modulation (wobbling) and shaping of the process beam.^{167,168} Additionally, more complex beam shaping approaches^{103,166,169} (that incorporate other degrees of freedom of light, besides just the amplitude) are promising strategies to improve process flexibility and productivity. Multibeam and multilaser systems with multiplexing (in polarization, wavelength or other functionalities) are well established within laser materials processing and the approach often focuses on processing identical features (i.e., hole drilling). Future applications will leverage these techniques for parallelization and processability (joining, printing) of multimaterial structures, graded interfaces, and intricate geometries. While incorporating more lasers can seemingly offer improved productivity, the total cost of ownership (including maintenance) and complexity of synchronizing their operation during printing should be considered, as the approach will result in diminishing returns beyond an optimal number of energy sources.

The dynamic nature of laser-melt pool interactions and consequent thermofluidic flows calls for time-scale dependent coupling to the addressed process features.¹⁶⁶ In this regard, the ability to dynamically shape/modulate/control high-power process laser beams using coherent beam combining (CBC)¹⁷⁰

has shown early promise. Using CBC, multi-kW laser beams can be modulated (in directions lateral and transverse to the process plane) up to tens of MHz without any moving parts.^{171,172} This approach will be crucial for a broad class of processes in the future, including AM, multimaterial joining, and cutting.^{173,174} Replacing traditional galvanometric scanning methodology will be crucial for improving parallelizability and reducing scanner inertia-induced defects during processing.¹⁷⁵ Arrays of multiple individually addressable and nondeflected low power diode laser beams and other types of areal processing methods have shown great promise in improving the rate of metal printing,^{175,176} and for relieving residual stresses during AM.¹⁷⁷ One bottleneck here is the laser damage that occurs in optics and devices that handle high fluences, but ongoing efforts and advancements in improving laser damage resistance in materials will be critical for future applications.^{178,179} In addition, diode laser array-based approaches include the need for larger optics as the diode array size scales, speed of communication between sub-components of the diode array system, which could limit the exposure strategy (orientation, dynamic scanning, etc.), heating of the electrical backplane (in pixelated modulator-based devices¹¹²), as well as the tradeoff between feature size and throughput.

Another important trend in laser processing is the gradual shift to visible wavelengths for handling materials that are highly reflective to near-IR wavelengths. Copper, for example, is an important material for electric motor components, heat management systems and heat-treating inductors.¹⁸⁰ Copper has a tenfold higher absorption at blue wavelengths compared to red or infrared wavelengths (a discussion of the relevant physics has been presented in Sect. 3.1.1). Printing pure copper through L-PBF generally requires up to ~1000 W to achieve densification of parts, due to the high infrared reflectivity and thermal conductivity of copper. However, developments in green and blue laser technologies have enabled printing copper with lower powers (e.g., using 200 W–1 kW for green laser and <100 W for blue laser in L-PBF), which minimizes the probability of damage to optics (due to back reflections) and provides greater flexibility for process control.^{180,181} Further improvements on this front will see other metals and alloys processed at these wavelengths.

Temporal modulation of the process laser beam using ultrashort-pulsed lasers can significantly enhance process flexibility. For example, today, ultrafast lasers are capable of pulse-on-demand up to GHz regimes. The ability to generate bursts of fs laser pulses at GHz repetition rates presents new possibilities for enhancing and controlling the laser machining quality. GHz burst mode processing offers choice of various parameters, including the number, duration, and energy of intra-pulses, the intra-pulse time interval and energy distribution shape, extending to packing GHz bursts into MHz trains. Ablation with GHz bursts of fs laser can lead to a mode that has been coined “ablation

cooling,” wherein the material removal is accompanied by limited heat accumulation.¹⁸² Characterization of the laser processed surfaces showed well-defined ablation features, suggesting diminished thermal effects in conjunction with augmented ablation efficiency (defined as the ablated volume per cumulative irradiated energy) by up to an order of magnitude. All of these are promising findings with potentially useful implications for applications, including thermally driven processes (e.g., micro-bonding, crystallization, and polishing), but also subtractive applications such as volumetric ultrafast laser processing.¹⁸³ *In situ* multimodal spectroscopic techniques¹⁸⁴ are needed to further improve understanding of ablation dynamics and leverage the capability for manufacturing applications. The combined application of cw and ultrafast lasers has shown great potential. For example, it has been shown that this approach implemented for AM can produce parts with precise sub-50 μm features, including slits and holes with high aspect ratios.¹⁸⁵ A recent thin-disk laser setup delivers ~0.7 kW in a diffraction-limited beam that superimposes cw and ultrafast radiation (1030 nm) via polarization multiplexing, allowing fast arbitrary adjustment of the power ratio. Work toward such a single, high-power hybrid laser source with dynamic and flexible operation modes will no doubt see immense growth in the coming years.¹⁸⁶

While current diode-pumped solid-state lasers have power limitations due to the need for frequency doubling, leveraging advancements in high-brightness semiconductor lasers^{187,188} will provide cheaper, more sophisticated parts needed for electromobility and circuitry. Besides the process flexibility offered by next-generation laser sources, robustness and precision during processing should also increase. Hence, maintaining a high laser power and beam pointing stability (<<1%) will be important. The industrial availability of ultrashort-pulse laser radiation in the deep UV range (4th harmonic) with high laser powers will enable higher precision in the surface processing of materials that are transparent in the visible wavelength range, such as glass. In semiconductor fabrication, extreme ultraviolet (EUV) lithography will continue to drive high-power laser development. Next-generation EUV sources may abandon today's 10.6- μm CO₂ lasers in favor of novel architectures, such as a diode-pumped solid-state petawatt-class laser employing thulium-doped yttrium lithium fluoride as the laser gain medium to produce light of 2- μm wavelength. The laser is designed with improved heat management to boost EUV plasma generation efficiency by ~10 $\times$.¹⁸⁹ Other ultrahigh-power petawatt-class laser sources are in operation or under construction at several facilities around the world, for applications in driving secondary (radiation and particle) sources, laser wake-field generation, and ICF.¹⁹⁰

As the demand for miniaturization in electronics, communications, and sensors intensifies, the need for integrated high-precision processing will necessitate the use of compact lasers that fit inside daily use technologies. While conventional semiconductor lasers are promising due to their compact

architectures, they lack the necessary fluence for processing applications, which is on the order of a gigawatt per square centimeter per steradian ($\text{GW}/\text{cm}^2/\text{sr}$).¹⁹¹ Microscale lasers such as photonic-crystal surface-emitting lasers (PCSELs), boast both high brightness (up to $\text{GW}/\text{cm}^2/\text{sr}$) and high functionality based on photonic crystal technology, and are appealing for future miniaturization needs.¹⁹² One envisioned application would be to have arrays of tiny (sub-mm) lasers that can be packed into compact devices for manufacturing or repair in space or in extreme environments (such as fusion energy chambers) and operated remotely. Similarly, nanoscale laser technology^{193,194} will continue to receive attention as their efficiency and integrability continue to be improved.¹⁹⁵

Emerging materials and manufacturing needs

Materials that can sustain extreme environments (high temperature, pressure, and cyclic loading) are a growing need in aerospace, defense, and energy applications. Enabling pathways to generate sustainable energy from fusion is one of the most important scientific challenges in the 21st century, and recent breakthroughs of net energy gain have highlighted the potential of fusion energy as a clean and viable form of energy.^{7,196} However, incorporating fusion as a practical source of power requires overcoming several fundamental challenges, including manufacturing new types of high-temperature, radiation-resistant metals and alloys. Plasma-facing components (PFCs) of practical fusion reactors (Tokamaks) require materials that can withstand harsh environmental conditions caused by high heat and neutron/ion flux inside the reactor chamber. Complex geometries involving multiple robust materials are needed for radiation resistance and fast heat extraction. High neutron fluxes (on the order of MWm^{-2}) inside PFCs produce damaging and poorly understood effects in materials, including degradation, thermal fatigue at material joints, tritium trapping, high stresses, sputtering, and embrittlement.¹⁹⁷ Studies have shown that the PFC material macrostructure, defects, and microstructure can greatly affect these properties, highlighting the need for their control to optimize performance.¹⁹⁸ Laser metal AM techniques will be crucial for rapid prototyping of PFC materials such as tungsten, tungsten alloys, HEAs, boron carbide, and carbon composites, with on-demand microstructures and engineered defects to facilitate design-build-test cycles in early stages.^{199,200} Other materials such as reduced activation ferritic-martensitic steels, copper alloys, oxide dispersion strengthened steels (as structural materials) are also important as structural and thermal components of a fusion reactor.¹⁹⁹ The high cost of target manufacturing is a key barrier for producing sustainable energy from inertial confinement fusion. Advanced AM techniques based on 2PP will enable new materials and novel target designs needed for economically viable fusion energy.²⁰¹ AM strategies will be critical in addressing materials needs for navigating the valley of death and accelerating R&D progress to deploy the first fusion power plant.²⁰² Developing materials that not only withstand extreme fusion environments, but can also be rapidly tested

(through benchtop, coupon-scale evaluations)²⁰³ and replaced or repaired (through laser processing) will be pivotal for the long-term viability of fusion energy.

Aerospace and defense sectors also demand materials that can handle extreme conditions, while posing strict requirements on reliability and weight.²⁰⁴ Advanced macroscale processing and AM approaches will continue to revolutionize this sector by enabling lightweighting (through lattice structure and topology-optimized) and improving manufacturability of conventionally hard-to-process materials such as refractories, titanium alloys, nickel superalloys, HEAs, and other materials that offer high-strength-to-weight ratios. Besides metals, composites such as carbon fiber-reinforced polymers, silicon carbide, and other ceramic matrix composites will drive the next generation of materials design, and laser processing techniques (such as cleaning, welding, cutting, and manufacturing) across multiple spatial scales will be important to obtain required mechanical properties (through optimized joining strength, deterministic microstructures, and defect-free components). Similarly, hypersonic aircrafts will require new and intricate types of designs in metals, refractory ceramics (such as carbides, nitrides, borides of transition metals) and other composites, which are outside the scope of conventional techniques (such as spark plasma sintering and hot pressing), but advanced manufacturing processes are well positioned to deliver.²⁰⁵ Techniques such as laser surface processing, DED, and high-speed laser cladding will continue to play a vital role in the repair and sustainment of existing fleet for aerospace and space vehicles, where fuel efficiency and payload capacity are paramount considerations.^{206,207} Asteroid mining using lasers has been proposed as a way to source metals such as nickel and iron, as well as volatile compounds such as water for use as rocket fuel.^{208,209} Improvements in laser architectures (to be able to withstand extreme conditions in space), reducing the weight and footprint, as well as beam divergence (to achieve longer propagation distances) of pulsed lasers will likely accelerate progress in such space-based laser materials processing applications.

The concept of multiple principal element alloys, commonly referred to as HEAs, has effectively revolutionized the design of potentially new and superior metallic alloys for structural applications.^{90,210} Such alloys develop fracture resistance due to the synergy of dislocation glide, stacking-fault formation, nanotwinning, and phase transformation that prolong strain hardening, hence simultaneously elevating strength and ductility leading to exceptional toughness.²¹¹ HEAs have demonstrated superior radiation resistance (significant suppression in nanofuzz growth) under He ion exposure, surpassing pure W.²¹² Certain nanocrystalline HEAs were shown to exhibit a threefold higher hardness and twofold higher specific strength compared to nanocrystalline Al and other conventional light alloys.²¹³ Some HEAs also possess very low stacking-fault energies ($\sim 3.5 \text{ mJ}/\text{m}^2$) compared to conventional steels ($\sim 18 \text{ mJ}/\text{m}^2$), which favors dislocation splitting, increases yield strength and minimizes the strength-ductility tradeoff.^{214,215}

In addition to their high cost, one major issue that has severely constrained their implementation has been the processing of these alloys. In this respect, laser AM techniques such as SLM and DED have shown promise in printing multiphase alloys that exhibit different phase stability than the wrought counterparts and provides a powerful combinatorial tool to scan the enormous compositional space of these materials.²¹⁰ However, HEA parts must resolve issues that arise from their compositional and microstructural complexity. Future work in the space will continue to focus on combined experimental and computational approaches to predict the microstructure and mechanical properties of laser processed HEAs, with the objective to optimize the processing and manufacturing protocols.

Widespread adoption of state-of-the-art manufacturing processes, particularly AM, will require addressing several economic challenges. For example, most AM-produced parts require post-processing steps prior to being qualification. The cost of processing for most AM printing methods can be significant, and are often more than the cost of printing. A typical AM-printed part goes through several steps after processing, including removal of support structures, machining, grinding, hot isostatic pressing and additional heat treatment, and post-processing accounts for 27% of the total production cost.²¹⁶ The combined application of process monitoring and control and hybrid processing methodologies (which provide improved control over thermal distribution, surface quality and defect evolution as discussed earlier, thereby improving fidelity of processed regions and alleviating the need for post-processing), in addition to design for AM (DfAM) frameworks,²¹⁷ will facilitate the push toward a first-time-right approach, which will be crucial in moving toward sustainable, scalable and cost-effective manufacturing in the future (Figure 5). While AM and emerging manufacturing approaches are likely not going to replace conventional processing methods, they will play a crucial role in exceeding state of the art in applications requiring functionality, high geometric complexity and performance in extreme environments. On the other hand, conventional technologies such as casting, forging, welding, and other formative processes will continue to play a dominant role in industry due to their technological maturity and cost effectiveness in high-volume production. A thorough assessment of tradeoffs between the different approaches to manufacturing will require a holistic supply chain, risk, and system-level cost analysis.^{218,219}

Over the next decades, materials will continue to become more functional and responsive, being able to sense and adapt to external stimuli.^{220,221} Such architected materials can be designed to be intertwined with multiple properties and functionalities across mechanical, thermal, electrical, and biological domains through hierarchical (spanning macro–micro–nanoscale domains) design strategies. However, achieving separation of scales within the same specimen and achieving desired mechanical responses necessitate fabrication techniques that possess a high build-volume to resolution ratio.

The emergence of rapid, scalable, and multimaterial processing techniques through ultrafast laser-driven 2PP and integrated optical strategies, such as dual-wavelength Xolography for volumetric, macroscale printing⁹⁵ and metalens array-based 2PP²²² for parallel processing, will be crucial and eventually replace serial, scanner-based techniques.^{220,223} Two-step (rather than two-photon) absorption 3D printing and its variants, which utilize cheap and compact cw diode lasers, will concurrently play an important role in efforts toward miniaturization, as photoinitiator system designs evolve to mitigate detrimental issues such as proximity effects.^{84,96,224}

Nano-/microscale laser processing will enable advances in high-power electronics, next-generation batteries, and quantum materials. For instance, SiC, GaN, AlN, diamond, and other ultrawide-bandgap semiconducting materials have been touted for RF electronics and nuclear battery (high-density, long-life power source that converts energy from radioactive decay into electricity) applications due to their high radiation hardness and superior conversion efficiencies.^{225,226} While such materials are hard to machine through conventional mechanical approaches, laser micromachining opens up the possibility to create micro-/nanostructures or laser-induced doping for increasing efficiency (higher power density), or for making compact and modular devices for deployment into space, deep sea, or extreme environments.^{226,227} Material candidates will also evolve as the need for miniaturized long-lasting (over decades) power sources garners more demand.^{226,228,229} Over a 50-year horizon, engineering quantum defects, embedding nitrogen-vacancy centers, and writing waveguide networks in optical circuits will need to be done with precision down to the atomic level, and at a scale that is comparable to today's semiconductor lithography industry. To this end, ultrafast laser processing is a promising route to overcome limitations of conventional lithographic approaches that are inherently planar and lack flexibility and capacity to implement such localized material modifications.²³⁰ For example, fs laser processing of Si to create point vacancies that emit single photons,²³¹ and reversible 3D laser printing of perovskite quantum dots within transparent media, are early feasibility demonstrations of embedded photonic architectures with active tunability.²³² Negatively charged nitrogen-vacancy (NV) centers in diamond are attractive as a qubit modality for quantum computation, due to their room-temperature operation, compatibility with nanofabrication techniques, and solid-state integration. NV centers are optically active and their spin states can be activated and read out, leading to applications in magnetometry, electrometry, and thermometry.²²⁸ Such NV centers have been created using fs pulses through surface processing, as well as in three dimensions.²³³ The orientation of NV centers have also been manipulated to lie along a specific crystallographic axis using fs laser annealing – paving the way for scalable quantum devices based on orientation of defects. Trapped-ion systems are another platform for quantum information processing due to their high coherence times and high-fidelity gate operations. Since the first demonstration of laser manipulation of qubits (in trapped ions), the development of

improved understanding of error sources and improvements in the precision of qubit logic gate has been driven by advanced optical control.²³⁴ Trapped-ion applications in quantum computing will move beyond conventional photolithography, toward on-demand 3D printing of traps for improved design freedom, precision, and functionality.²³⁵ These studies highlight the evolving role of lasers beyond conventional micro-fabrication, pushing it toward a broader class of optoelectronic, quantum, and reconfigurable systems. The future of manufacturing as envisioned in the Industry 4.0 paradigm will rely on the development of innovative materials and processing technologies, driven by increased interconnectivity and smart automation.⁵ Ongoing innovations in laser-based material design and processing capabilities, including the widespread adoption of digital infrastructure, data-driven machine learning tools, and AI-powered operation models will predominantly drive the next wave of manufacturing R&D in the coming decades.

Conclusions

Laser materials processing has positioned itself as a foundational platform for modern manufacturing and an enabler of emerging technologies. Powered by parallel advancements in laser sources, optoelectronic devices, process control techniques, predictive modeling, and materials science innovations, today's materials processing arsenal enables cw laser-driven macroscale modifications (such as welding, cutting, and joining) to nanoscale circuitry carved using fs lasers. This article highlights how classic cutting and joining, additive/subtractive manufacturing, and hybrid machining tools are indispensable for current research and manufacturing needs of a wide class of materials across disparate spatial scales. Multi-kilowatt, continuous-wave sources have improved throughput for welding, cutting, and printing, while high-fluence, short and ultrashort-pulsed lasers have improved the ability to machine fine features by packing high peak energy densities in small focal volumes and minimizing thermal artifacts. This article makes a case for how such advances in laser technologies are crucial for processing materials that thrive under extremes of temperature, radiation, mechanical load, geometric complexity, and functionality, as we race toward a future that demands sustainable, adaptive, miniaturized, and efficient processing capabilities. Together, these innovations will pave the way for meeting society's grand challenges in fusion energy, aerospace, defense, optoelectronics, biomedical devices, and quantum processing.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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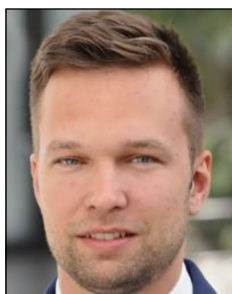
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