Process and product innovation in electric mobility enabled by photonics

Laser-based manufacturing processes enabling the use of sustainable materials and recycling of battery systems as well as flexible manufacturing of electronics

Ali Gökhan Demir

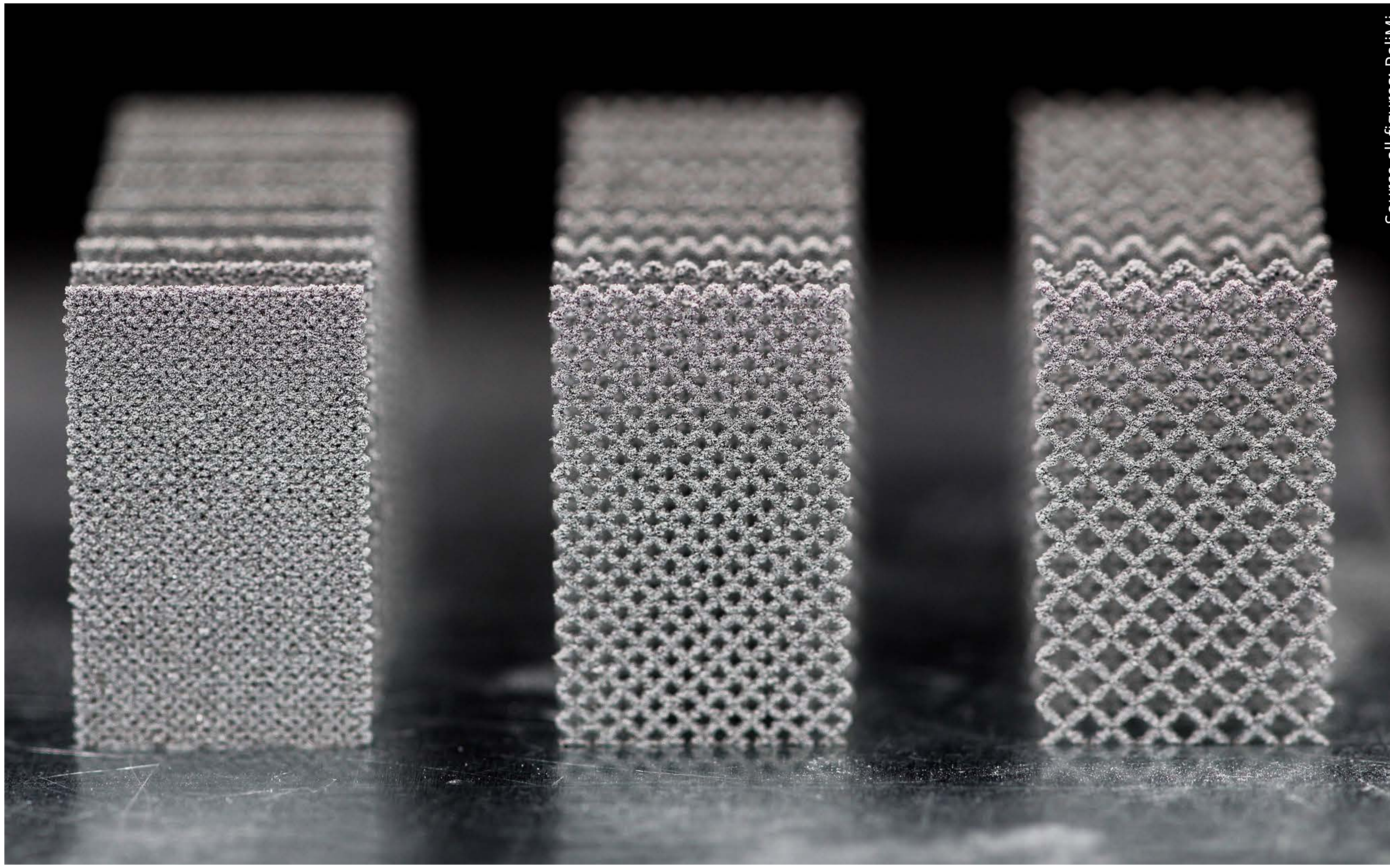

Fig. 1 Additively manufactured zinc anodes with controlled porosity can provide a sustainable route for long-term energy storage systems. Specimen dimensions are 9 mm × 15 mm × 0.4 mm

Lasers provide flexible manipulation of energy input for material transformation in a digital manner. The advent of electrification in mobility embedded these technologies in critical components such as the drive train and the energy storage systems. Lasers offer more solutions for this emerging industry, where process and product innovation is often achievable through well-known and novel ways of interaction between material and light. At Politecnico di Milano, laser based-manufacturing tools are exploited for next-generation of electric mobility with a wide range of applications from biodegradable batteries to material recovery systems and flexible electronics.

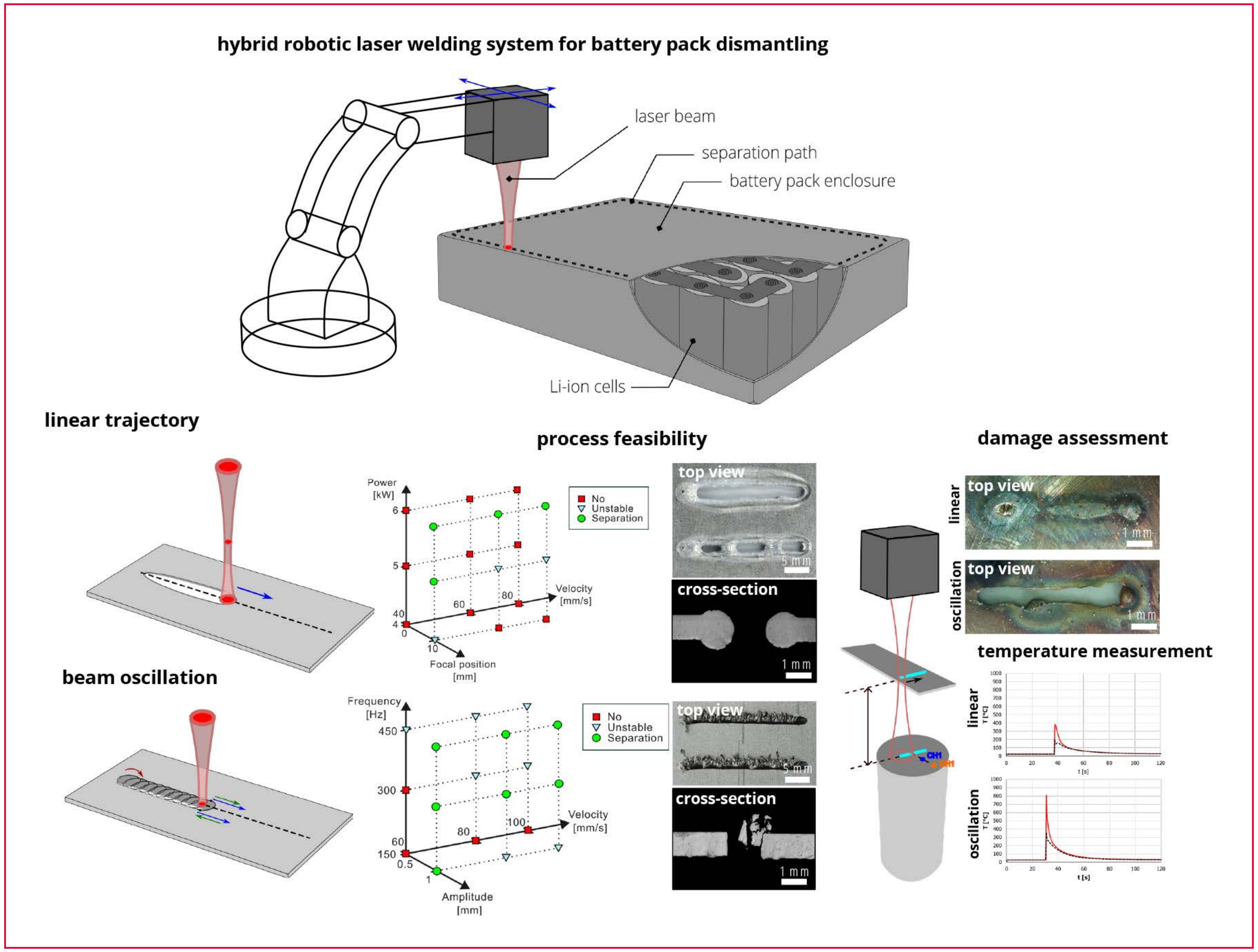

Fig. 2 Hybrid use of a robotic laser system for welding and dismantling of battery packs – the laser beam used for welding can be exploited for remote separation of the battery pack enclosure with limited damage on the underlying cells

The electrification of mobility poses challenges and opportunities to the vehicle manufacturers. Laser based manufacturing processes have been widely adopted in key products of the electric vehicles (EVs). Powertrain and energy storage systems already exploit laser cutting, welding, heat treatment, and surface structuring processes. Some of the key applications of laser-based manufacturing processes are welding of hairpins and stator laminates of the electric drives, electrode structuring, cutting, and welding in Li-ion batteries, as well as the production of the battery packs using the combination of these processes. The electric vehicle industry is now looking into robust solutions exploiting the digital tool combined with monitoring solutions and artificial intelligence. The electric mobility in the meanwhile also calls for new solutions for problems that still require attention that ranges from increased range of vehicles, use of environmentally sustainable solutions as well as a view towards the end-of-life of these products. Photonic solutions based on lasers, optical measurement, and monitoring devices from this perspective can play a key role in product and process innovation. At Politecnico di Milano, the Laboratory for Laser Applications, SITEC, looks towards the development of new processes enabling new products and solutions for electric mobility exploiting the increased availability of laser-based manufacturing solutions in the industry.

Electric mobility as an emerging field open to innovation

The manufacturing process in the automotive sector has long been driven by safety concerns as well as the economy of production. Vehicles powered by internal combustion engines have been developed over the years into new models, while some of the main concepts of production have remained the same or changed only modestly. The so-called industrial revolutions have had their direct interaction with this sector, starting from the use of steam power to the development of the production line, the adoption of industrial electronics, and finally the introduction of sensors in manufacturing processes. One could argue that changes in the automotive industry align with paradigm shifts in manufacturing, evolving alongside industrial revolutions. Electrically driven vehicles, from this perspective, represent a highly demanding change for the industry, where manufacturing solutions have to be developed from scratch. While such conditions pose a great challenge for the manufacturing industry, there are also opportunities to develop new products for an industry where novelty has traditionally been adopted slowly.

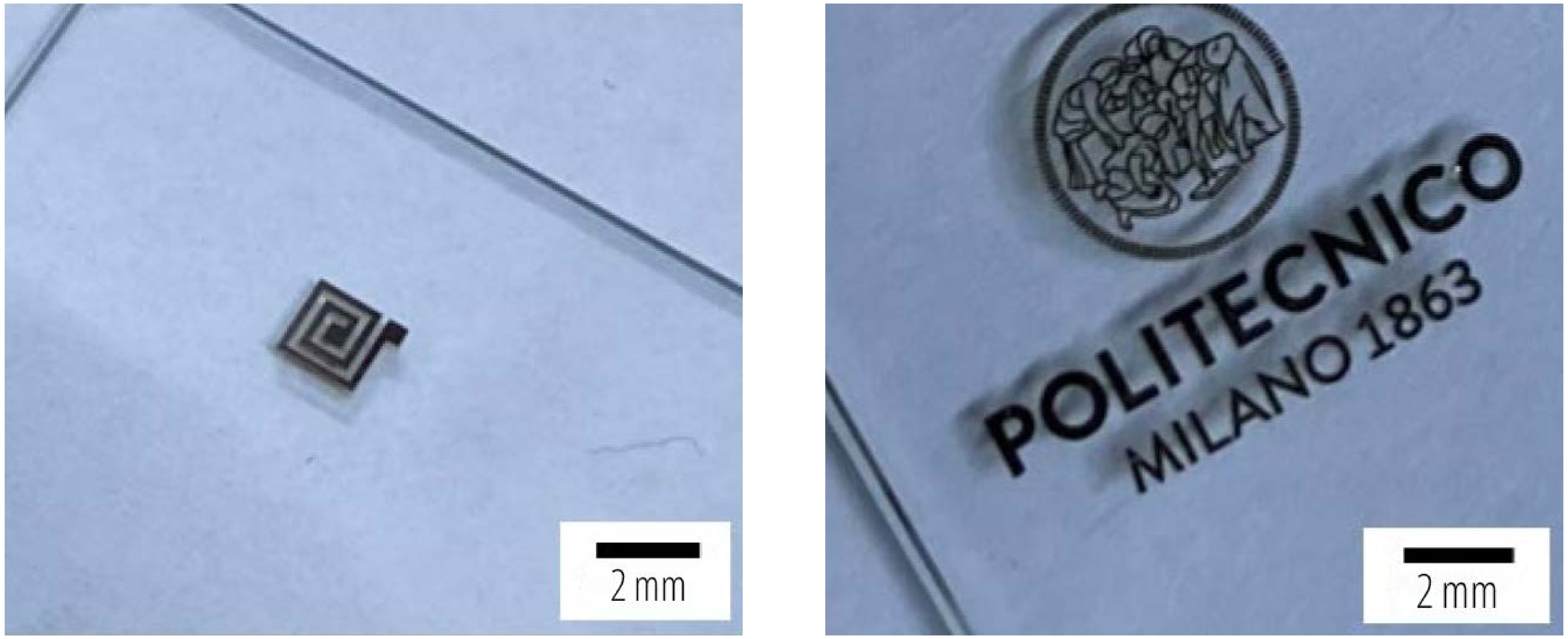

Fig. 3 Examples of flexible deposition of electrically conductive copper deposited on glass via laser-induced reverse transfer showing an example of an electrical circuit and the logo of Politecnico di Milano.

Lasers have proven to be a key tool for addressing manufacturing challenges and are already widely used for welding, cutting, and heat treatment operations in electric vehicle manufacturing. On the other hand, laser-based manufacturing processes can help drive innovation by enabling new products through processes and materials that are new to this sector. In the following sections, we examine some of these novel product and process combinations, utilizing well-known but previously underexploited laser techniques.

Zinc: enhanced geometries enabled by laser-based AM

Zinc-based batteries have garnered significant attention as a promising alternative to lithium-ion systems, primarily due to zinc's abundance, cost-effectiveness, and environmental friendliness. However, challenges such as electrode polarization and dendrite formation have hindered their widespread adoption. To address these issues, research at Politecnico di Milano has focused on integrating additive manufacturing (AM) techniques, particularly laser powder-bed fusion (LPBF), to fabricate pure zinc electrodes with tailored properties [1].

LPBF enables the production of intricate zinc structures by selectively melting zinc powder layers using a laser. This approach allows for precise control over the electrode's geometry and porosity, which are crucial factors influencing electrochemical performance. By adjusting parameters thin-walled zinc structures with thicknesses ranging from 200 to 500 µm and increased surface area. LPBF can be used especially to tailor the topology of the battery exploiting stochastic and designed porosity. In particular, lattice structures with different levels of pore size and density can be used to tailor the electrochemical performance of the batteries (Fig. 1).

Preliminary electrochemical evaluations of these additively manufactured zinc electrodes have been conducted in both phosphate-buffered saline (PBS) and 6M KOH solutions. Cyclic voltammetry and galvanostatic charge/discharge tests have demonstrated the electrodes' potential as anodes in aqueous battery systems. The ability to fabricate zinc electrodes with controlled architectures via LPBF opens new avenues for designing batteries with enhanced performance, potentially overcoming the limitations associated with traditional manufacturing methods. In addition to LPBF, the research has explored the influence of core/ring laser beam shape configurations to understanding how different beam profiles affect the melt pool dynamics and solidification processes is essential for optimizing the additive manufacturing of zinc electrodes.

Collectively, these advancements highlight the potential of additive manufacturing techniques, especially LPBF, in revolutionizing the production of zinc-based battery electrodes. By enabling precise control over electrode microstructures and compositions, these methods pave the way for the development of high-performance, cost-effective, and environmentally friendly solutions, exploitable for long-term energy storage systems.

Reuse and recycling of battery systems using laser-based manufacturing

The growing demand for electric vehicles has intensified the need for efficient battery recycling and reuse strategies. Laser-based manufacturing techniques have emerged as a promising solution, offering precision and adaptability in dismantling battery systems and recovering valuable materials. Robotic systems equipped with high-power laser sources can efficiently disassemble battery packs, enabling separation of components (Fig. 2). This approach minimizes direct human contact with hazardous materials, enhancing safety while reducing the risk of short circuits during disassembly.

Beyond dismantling, laser ablation techniques facilitate the recovery of critical metals such as lithium, cobalt, and nickel from electrode foils. Unlike traditional chemical processes, which often involve hazardous waste and high energy consumption, laser ablation provides a cleaner and more efficient alternative. The precision of laser processing ensures high-purity material extraction, making the recovered elements suitable for reuse in new battery production.

The adaptability of laser systems allows for hybrid applications across different stages of a battery's lifecycle. For instance, robotic welding systems initially used for assembling battery casings can be repurposed for laser-based separation processes during recycling [2]. This dual-purpose functionality supports a circular economy by optimizing resource utilization and reducing overall costs. Recent advancements in laser beam shaping will allow for a better control over the quality minimizing the damage on the recovered material and increase productivity. Integrating laser-based techniques into battery reuse and recycling presents a sustainable pathway for the EV industry. By improving the precision, efficiency, and adaptability of disassembly and material recovery, these technologies align with environmental conservation efforts while supporting the transition to a more resource-efficient energy storage ecosystem.

Flexible manufacturing of electronic devices exploiting laser-based deposition and ablation processes

The transition to electric mobility requires continuous advancements in power electronics, sensors, and energy management systems. To meet the demands of high efficiency, miniaturization, and reliability in electric vehicles, innovative manufacturing techniques are essential. Laser-based deposition and ablation processes offer a precise and flexible approach to fabricating electronic components, enabling the integration of high-performance materials while minimizing waste and processing time.

Laser-assisted electrodeposition of binary metallic alloys from water-based electrolytes provides an environmentally friendly and efficient method for producing advanced electronic materials [3]. Laser processing enables the controlled deposition of thin films with tailored electrochemical properties, crucial for energy storage and conversion systems in EVs. These materials are particularly valuable for battery management circuits and fuel cell applications, where enhanced conductivity and durability are required to optimize performance and extend lifespan.

Laser-induced reverse transfer (LIRT) of bulk metal targets using ultrafast lasers presents a highly controlled approach for microelectronics applications [4]. Copper is a key material in the interconnects and wiring of power electronics in EVs, where high electrical conductivity and precision patterning are essential. The LIRT technique enables the transfer of pure copper with minimal thermal damage, ensuring reliable performance in high-frequency circuits and compact power management systems that are vital for efficient energy distribution (Fig. 3).

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Additionally, laser-induced forward transfer (LIFT) with high resolution enhances the fabrication of intricate microelectronic structures required for next-generation EV components [5]. LIFT allows for the precise placement of functional materials, enabling the development of miniaturized sensors and control systems for vehicle electrification. These sensors play a crucial role in monitoring battery health, temperature regulation, and real-time energy consumption, ensuring optimal efficiency and safety in electric mobility.

By integrating these laser-based deposition and removal techniques, manufacturers can enhance the performance and sustainability of electronic components used in EVs. These innovations contribute to the ongoing transformation of the automotive industry by enabling the production of high-efficiency, compact, and reliable electronic systems, ultimately supporting the widespread adoption of electric mobility.

Outlook

Laser-based processes will remain key enablers in the next generation of electric mobility. Laser systems and manufacturing equipment have become more economical over the years, overcoming a key limitation to the wider adoption of laser-based manufacturing processes. Today, the next obstacle appears to be the expansion of industry knowledge regarding the use of lasers and mastering laser-based manufacturing techniques. The next generation of manufacturing systems will have to be more user-friendly, from operation to maintenance. Simulation models and artificial intelligence will be key ingredients in paving the way for processes that can self-calibrate and maintain quality.

Another relevant aspect that will render photonic tools and lasers in principle as key tools for the future mobility regards the energy usage. The use of lasers combined with novel beam shaping solutions in space, time, and wavelength is likely to provide key changes in heating-based processes where furnaces are substituted. Another important factor where laser-based manufacturing may reduce energy consumption is related to the contact-free nature of photonic tools. The adoption of lasers in existing welding and cutting applications may reduce the energy consumption through reduced energy used for fixing and handling parts that is yet to receive more attention form an industrial perspective. ■

Politecnico di Milano – SITEC

The department of mechanical engineering's Laboratory for Laser Applications, SITEC, is equipped with several high power, high brightness, continuous wave or pulsed lasers and industrial automation systems that are integrated for different applications. Over the years, SITEC has developed successfully processes for macro and micro applications such as laser welding, cutting, cladding and additive manufacturing, as well as studying design rules for laser based manufacturing. The developed research activities serve several sectors namely, automotive, aerospace, energy, biomedical, white-ware and electronics. Close collaborations with industrial partners have been developed, as technological transfer to companies constitutes an important part of the activities.

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