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EDITORIAL

# The multifaceted path to sustainable metallurgy: process innovation, circular economy, and digitalization

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This special issue of *Matériaux & Techniques* is a curated selection of the most impactful papers from the European Steel Technology and Application Days (ESTAD) 2025, organized by the Italian Association for Metallurgy (AIM). The selection reflects the conference's core mission: to chart the trajectory of the steel industry toward a future defined by decarbonization, digitalization, and advanced material performance.

The connection between the papers presented at ESTAD and the scope of *Matériaux & Techniques* is deeply organic. For decades, this journal has served as a critical forum for the intersection of materials science, processing engineering, and their environmental implications. The steel industry is currently at a pivotal moment, undergoing a transformation arguably more profound than any since the Bessemer process. The manuscripts featured in this issue capture this transition, moving from foundational research in hydrogen-based metallurgy to the practical application of artificial intelligence in rolling mills, all while maintaining a rigorous focus on material properties and microstructural control.

The selection opens with a quintessential example of this duality: "Performance of a HSLA steel produced via EAF and Arvedi ESP$^{TM}$ process route for the service in gaseous hydrogen." This work addresses the critical challenge of material compatibility in a hydrogen economy—a cornerstone of future sustainable energy systems—while utilizing a near-net-shape casting and rolling process renowned for its energy efficiency. It directly speaks about the processing routes to define service performance in emerging applications.

The theme of process innovation for sustainability is further amplified by two complementary papers. "Improving sustainability of cold rolling of low-carbon steels via oil free lubricants" tackles the imperative to eliminate hazardous industrial effluents, while "Assessment of the natural absorption of $CO_2$ performed by steelmaking slag" explores the concept of steel production sites not merely as emitters but as potential carbon sinks through accelerated carbonation of by-products. These studies are emblematic of the circular economy principles.

The theme of industrial symbiosis is given a dedicated focus through the paper "Recent achievements of Industrial Symbiosis in the steel sector based on the Symbio-Steel project." This contribution moves beyond theoretical frameworks to provide empirical evidence of how cross-sector collaboration—sharing energy, water, and by-products—can transform a steel plant from an isolated industrial entity into a central node in a regional circular ecosystem.

On the frontier of process metallurgy, the selection includes "Advancing hydrogen plasma smelting reduction: Experimental insights from a pilot plant." This paper represents the vanguard of the sector's decarbonization efforts, offering a glimpse into a future where iron ore is reduced using hydrogen plasma, eliminating direct $CO_2$ emissions from the reduction step.

Alongside these macro-level innovations, the collection maintains a deep appreciation for the microstructural science that defines material excellence. Papers such as "Role of vanadium in welding of flat products in high strength low alloyed steels: microstructure and mechanical properties" and "Improvement of low temperature toughness of low-alloy steel forgings by intermediate intercritical quenching" demonstrate that as processes become more sustainable, the demand for superior material performance does not waver. Understanding the nuanced role of microalloying elements and advanced heat treatment cycles remains essential for producing the high-performance steels required for next-generation infrastructure and transportation.

Finally, the integration of digitalization is showcased in "Multi-functional simulation system for continuous hot bar rolling: development and industrial application." This paper illustrates how the steel sector is leveraging simulation and data to optimize complex processes, reduce waste, and accelerate product development—a crucial component of the Industry 4.0 paradigm that is increasingly central to both ESTAD and the pages of this journal.

Taken together, these papers offer a microcosm of the contemporary steel sector. They illustrate that the path to sustainability is not a single technology but a multifaceted

strategy involving radical new reduction processes, circular economy principles, enhanced material efficiency, and the digitalization of production. By presenting this selection from ESTAD 2025, *Matériaux & Techniques* reaffirms its role as a premier platform for disseminating the scientific and technical advancements that will define the materials of the 21st century. We extend our gratitude to the authors for their contributions, the AIM for their partnership, and the reviewers for ensuring the high quality of this special issue.

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