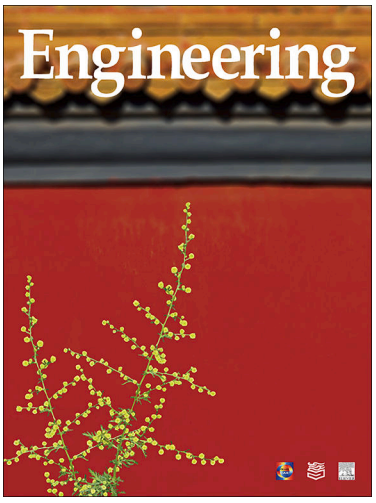
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Editorial

Frontiers of Extreme Manufacturing: From Atomic Precision to Autonomous System

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Editorial

Frontiers of Extreme Manufacturing: From Atomic Precision to Autonomous System

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Every major leap in engineering science and human civilization has fundamentally hinged on pushing past the perceived boundaries of manufacturing. Today, extreme manufacturing represents the forefront of this endeavor, utilizing advanced manufacturing technologies and high-end equipment to enable the fabrication of extreme-scale, high-precision, and high-performance structures, devices, or systems, as well as scientific lab equipment that can simulate extreme physical environments or conditions. By transcending classical engineering boundaries and addressing atypical phenomena that emerge at extreme dimensions, extreme manufacturing fundamentally reshapes how energy and matter interact.

To capture this critical transition, this Special Issue of *Engineering*, entitled "Frontiers of Extreme Manufacturing", brings together 14 pioneering contributions that map the new theory, process, metrology, characterization, equipment, conditions, and system integration in extreme manufacturing, as well as materials, structures, and devices with extreme functionalities. It highlights how innovations in microscopic mechanisms support the cross-scale integrated manufacturing of materials, structures, and functions, which in turn demands the accelerated deep fusion of the entire manufacturing chain toward high-fidelity multi-physical perception, digital twins, and cognitive closed loops.

At atomic and molecular scales, material removal and surface processing are shifting from macroscopic shear deformation toward targeted bond manipulation driven by coupled physical and

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chemical fields. As demonstrated by Fengzhou Fang et al., nanoscale electric fields can be deployed within confined aqueous menisci to lower the energy barrier for targeted cleavage of covalent bonds, while Zhigang Dong et al. show that synergistic photoelectrochemical oxidation disrupts native lattices to drive sub-nanometer removal through stress- and temperature-assisted phase transformations. Concurrently, Hui Deng et al. reveal that enzyme-catalyzed hydrolysis provides an abrasive-free, chemically specific route to cleave and refresh surface-active bridge bonds for atomic-level planarization. By modifying interfacial charge distributions and density of states, electric fields further reshape potential energy surfaces, where Yu Sun et al. review the continuous and reversible *in situ* modulation of microscopic friction, atomistic slip, and phase stability across low-dimensional heterostructures, complementing the work by Benny C.F. Cheung and Chunjin Wang et al. on resolving concurrent electromagnetic and matter-reorganization phase transitions during ultrafast laser scanning. In addition, Kun Cao and Rong Chen et al. demonstrate that area-selective atomic layer deposition coupled with interface-driven cluster migration can effectively anchor sub-nanometer metallic catalysts against high-temperature sintering.

This atomistic control supports the simultaneous synthesis of materials, structures, and functionalities tailored for extreme environments. The traditional dichotomy between mechanical workability and ultra-high-temperature resistance has been reconciled by Lin Li et al. through engineering non-stoichiometric metastable phases and exploiting rapid solidification during additive manufacturing, producing alloys that combine room-temperature damage tolerance with the capability to transform into single-phase refractory ceramics at extreme temperatures above 4000 K. On the structural scale, Hailong Cui and Yanquan Geng et al. show that nanomechanical sectioning overcomes the native optical selection rules of van der Waals semiconductors via controlled interlayer gliding, imparting superior optoelectronic sensitivity under severe mechanical strains. These materials innovations converge with high-integrity aerospace mechanisms surveyed by Haitao Yu and Hongjian Zhang et al. for vertical recovery and multi-pass aerothermal re-entry, alongside thin-film perovskite photovoltaics reviewed by Jung-Ho Yun and Lianzhou Wang et al. to counter the coupled challenges of thermal shock, high-vacuum outgassing, and cosmic particle irradiation through self-healing lattice dynamics. In each case, material architecture and macroscopic mechanics are tailored to match their extreme operational boundaries.

Realizing such a manufacturing lifecycle with high repeatability requires a digital thread that links microscopic material behavior to automated machine control. Bypassing the limitations of empirical process tuning, Joon Phil Choi and Yong-Jin Yoon et al. utilize self-supervised representation learning and attention-driven vision frameworks to resolve microscopic deposition anomalies under limited labeled datasets. By coupling edge-computing backbones with real-time process monitoring, Yuebing Guo et al. demonstrate how live digital twins execute millisecond-level inference and direct numerical-control adaptation, translating transient dynamics into closed-loop corrective actions. Meanwhile, Xiangqian Jiang and Wenjuan Sun et al. establish complete causal chains from image quality to reconstructed surface topography via two-dimensional spatial frequency response modeling in X-ray computed tomography, while Wei Liu et al. develop hybrid multi-axis optical fusion metrology to overcome long-standing metrological resolution barriers for complex geometries and internal lattices.

Notwithstanding these achievements, substantive theoretical and technological barriers remain. Robust non-equilibrium modeling across disparate spatio-temporal scales remains computationally intensive, while scaling atomistic precision to high-throughput, defect-free industrial throughput presents enduring challenges.

The path forward will be forged by atom-to-system integration, fully autonomous self-learning manufacturing platforms, and collaborative human-AI ecosystems. By gathering these foundational studies, extreme manufacturing seeks to catalyze the global engineering community to explore uncharted physical regimes, providing the foundational science and technological capabilities needed to engineer a sustainable and transformative future.

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