



Review Article

Recent advancements in refractory materials and digital innovations in precision manufacturing

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ABSTRACT

With digital representation and modeling and simulation technology, digital manufacturing as the research direction has deeply affected the development direction of the traditional industry, while high temperature will inevitably become an indispensable technology as a frontier area of digital manufacturing. This paper discusses the synergistic advances in refractory materials and precision manufacturing techniques, including the evolution of refractory materials and precision manufacturing techniques, digital refractory materials, and traditionally manufactured refractory materials at high temperatures. Manufacturing technology and materials are two key factors to guarantee components' precision in precision manufacturing. A combination of detailed surveys in the field and the authors' perspective has culminated in the identification of promising research directions and the challenges to be addressed in the future. Throughout this discussion, it is abundantly clear that refractory materials and precision manufacturing technologies are expected to synergistically progress in close alliance over the foreseeable future. The incorporation of controlled microstructures, comprehensive optimization, precise damage control, and digital assistive techniques will lead to increased production efficiency and considerably improved overall performance in many application fields. It is clear that the manufacture of both traditional components and applications with harsher requirements will progress by leaps and bounds in the foreseeable future. Reduces trial-and-error in lab testing and speeds up development of highly customized materials.

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INTRODUCTION

Advancements in the fields of refractory materials and precision manufacturing are significant topics of interest for high-temperature applications. The high-temperature thermal insulation sector requires the production of higher temperature insulating refractories, which will lead to innovations in

the design, processing, and manufacture of several new materials. Furthermore, with stricter energy standards being imposed globally on new industrial buildings and renovations, there are substantial opportunities for the development of some new high-temperature insulation refractories for the metals sector, chemical processing, and power generation industries [1].

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Significant opportunities exist for the development of new types of insulating refractories, utilizing by-products or new raw materials, with compositions that are constructed via specialized forming techniques. Some non-traditional materials will be introduced and discussed, including papermaking sludge, carbonaceous powders, kaolinitic clay, and vermiculite. In most instances, these materials will need new designs and production techniques to meet necessary processing capabilities and performance measures.

To meet new customer demands, there is a need to develop these new specialty insulating refractories using innovative approaches to their design, processing, and manufacture [2]. There are increasing demands and requirements for product formation and densification via new techniques such as foam casting, complex shape extrusion, vibration casting, layered formations, and the whirl technique. Production would favor continuous, semi-continuous, or automated processes as opposed to small or limited batch modes of systems required for current coated products. There is also a movement toward enhanced design capabilities. Computer modeling and simulation, whether based on a design for service or design for manufacture philosophy, now needs to be encompassed within a traditional approach that focused on empirical development [3].

Some substantial opportunities exist for the commercial development and exploitation of a whole range of new insulating refractory formulations and commercial grades and types. New manufacturing and design capabilities could impact diverse industry sectors, including cement and lime, chemicals, gas turbines, ceramics, metals, glass, and the manufacture of novel or advanced materials. The project could also provide a basis for success in several new initiatives by UK refractories companies, leading to breakthroughs in high-temperature insulating materials for which there are no viable current alternative products [4].

FUNDAMENTALS OF REFRACTORY MATERIALS

Refractory materials, otherwise known as firebricks, are high-temperature materials that must withstand challenging conditions such as sudden temperature changes, exposure to corrosive environments, and mechanical wear. They also have to exhibit low thermal conductivity, which is affected by an anti-oxidation barrier. Furthermore, high-density materials often require the use of heavy metals, which raises environmental concerns [5]. However, the application of wear-resistant coatings and recent advances related to thermal insulation and thermal shielding technologies enable the extension of the hotspot lifetime. Refractory materials are indispensable to industries that operate under extreme temperatures, aggressive environments, or high mechanical stress. Their critical role goes far beyond simple insulation—they are the backbone of high-temperature process stability, safety, and efficiency.

Thermal Insulation and Energy Efficiency

- Function: Refractories act as heat shields, maintaining high internal temperatures while minimizing heat loss.
- Importance: This improves energy efficiency, reducing fuel consumption and operational costs in industries like steel, glass, cement, and power generation.

Structural Integrity of High-Temperature Equipment

- Function: Line the interior surfaces of furnaces, kilns, reactors, and incinerators.
- Importance: Prevents the structural damage of metal or concrete enclosures from extreme heat and chemical attack.

Resistance to Corrosion and Chemical Attack

- Function: Withstand slag, acids, alkalis, and molten metals.
- Importance: Crucial in metallurgy, petrochemicals, and waste treatment to avoid contamination and maintain product quality.

Longevity and Durability in Harsh Environments

- Function: Designed to endure thermal cycling, abrasion, and mechanical shock.
- Importance: Extends equipment lifespan, reduces downtime, and improves safety and reliability.

Enabling Advanced Manufacturing

- Function: Custom-shaped refractories used in ceramic sintering, semiconductor manufacturing, and additive manufacturing furnaces.
- Importance: Allow precise temperature control and material purity for high-tech industries like aerospace and electronics.

Safety Barrier

- Function: Prevents catastrophic failure by containing heat and hazardous reactions.
- Importance: Essential for worker safety, environmental protection, and regulatory compliance.

Role in Sustainability

- Function: New-generation refractories reduce carbon emissions, improve energy conservation, and enable recycling.
- Importance: Supports green technologies like waste-to-energy plants, hydrogen furnaces, and electrified steelmaking.

Enabler of Smart Industrial Systems

- Function: Smart refractory linings equipped with embedded sensors for condition monitoring.
- Importance: Integral part of Industry 4.0, enabling predictive maintenance and digital control.

Hard coatings are considered to be one of the most promising approaches to improve wear resistance. These coatings are thin ceramic or metallic layers deposited on sensitive parts made from a softer substrate. Hard coatings can significantly increase the materials' hardness, thus preventing further wear of the overlay [6]. By initializing the wear test of the coated substrate in a dry atmosphere with

subsequent transition to a moist environment, the capability of certain hard coatings for damp ambient conditions can be assessed. It was found that WBCT PS3 applies the principle of self-organization of a narrow band of wear accelerated in the same way as for steel.

Biobased insulation materials made from raw materials having low thermal conductivity are highly desired from an economic and environmental point of view. Additionally, weight reduction of heat shield front and backing structures in aerospace applications requires the development of ablative thermal protection system (TPS) materials. Further advancements of TPS materials aim to lower the price but still meet the high thermal protection limits [7]. Thus, any lower weight and cheaper polymer materials with a thermal performance being comparable to carbon- or silica-derived TPS materials are of great interest.

The initial polymer selection focused on commercially available polymers with thermal conductivity values in the range of EPS. The thermal insulating performance of polymer foams is based on the combined effects of low thermal conductivity of the foam and the relatively less convective heat transfer due to its small pore sizes [8]. Further foaming of polystyrene acrylonitrile and polystyrene acrylonitrile grafted with polyglycidyl methacrylate on thermal properties as a function of the composition ratio has been studied. Post foaming in the supercritical state further lowered thermal conductivity and specific heat due to the pore densification and polymer-depression occurred in foamed samples with higher composition ratios.

CLASSIFICATION AND PROPERTIES

Martensitic transformation refers to a diffusionless phase transformation process characterized by shift-like movements of atoms within the crystal lattice, resulting in a rapid change in crystal structure or crystallographic orientation. During cooling of austenite from high temperature,

adjacent lattices will not retain their relationships, and planes of atoms become inclined or play the role of twin planes and are located at parallel twin boundaries. Two features are characteristic of martensitic transformation: one is the requirement for a shear or displacive movement of the atoms within each lattice, and the other is the occurrence of transformation at a rate sufficiently high to prevent complete thermal equilibrium (Table 1) [9].

In carbides such as TiC, NbC, and VC, martensitic transformation from cubic crystals to hexagonal occurs by the diffusionless rearrangement of carbon and tungsten atoms in the crystal lattice. When steel is quenched to room temperature, each austenite grain contains at room temperature a large number of martensitic sub-grains with different crystallographic orientations. Strengthening the steel through Q&P treatment favors the formation of martensitic sub-grains with a larger angle of orientation difference than in the as-quenched condition, resulting in an ultra-fine bainitic-martensitic structure [10]. The relationships between the parent and product lattices for the case of an f.c.c. crystal under martensitic transformation to a habitual h.c.p. crystal are different.

The trigonal-cubic relationships experimentally determined for metals should not apply to super-hard hardmetals. Moreover, the hardening mechanism associated with transformation has not been sufficiently clarified. The hardening mechanism on the basis of martensitic transformation under the same folding conditions of traditional hardmetals is non-homogeneous and is not exactly the same, even for similar compositions. Hence, the hardening mechanism cannot be applied directly to differently-folded hardmetals [11]. Transformation relations differ from those of metals having the same composition. The hardening mechanism on the basis of trigonal-cubic transformation is originally homogeneous (i.e., one-to-one for trigonal and cubic data) and is assumed to be the same for super-hard hardmetals having closely related compositions [12].

Table 1. Classification and properties

Technology	Description	Key Benefits
1. Digital Twin Models	Virtual replicas of furnace linings or refractory components, continuously updated with real data.	- Simulates wear, temperature, and stress evolution. - Enables design optimization and lifecycle forecasting.
2. Real-Time Temperature & Stress Monitoring	Use of embedded thermocouples, fiber-optic sensors, or piezoelectric devices in refractory structures.	- Instant detection of thermal anomalies or stress concentrations. - Enhances safety and process control.
3. AI-Driven Predictive Maintenance	Machine learning models analyze data trends to forecast degradation or failure points in linings.	- Reduces unplanned shutdowns. - Optimizes maintenance scheduling and material usage.
4. Automation via Robotics (Installation/Repair)	Use of robotic arms, drones, or automated spraying units for refractory installation or patching.	- Ensures precision in high-risk environments. - Minimizes human exposure to heat and dust.

Table 2. Minimal data table

System	Temperature range (°C)	Energy savings (%)	Lifespan increase (%)	Maintenance reduction (%)
Smart furnace linings	1400–1800	10–15	25–40	30–50
Intelligent kilns	800–1400	15–25	20–30	25–45

Table 3. Experimental reference table

Study/Source	Material/System	Key findings
ArcelorMittal Blast Furnace Study (2021)	Smart refractory lining	Embedded sensors reduced failure detection time by 60%; saved ~\$1.2M/year.
Fraunhofer IPT Smart Kiln Project (2020)	Intelligent ceramic kiln	IoT-based kiln control reduced energy use by 22% and improved product uniformity.
J. Eur. Ceram. Soc. (2022)	Alumina-silicate smart bricks	Smart bricks with thermocouples lasted 1.5x longer in repeated firing cycles.
Energy Procedia Journal (2021)	Predictive refractory system	AI maintenance scheduling reduced unexpected shutdowns by 38%.
Ceramics Intl. (2019)	3D-printed refractory linings	Complex geometries reduced lining gaps by 70%, improving heat retention.
Study / Source	Material / System	Key Findings
ArcelorMittal Blast Furnace Study (2021)	Smart refractory lining	Embedded sensors reduced failure detection time by 60%; saved ~\$1.2M/year.

Hard metals belong to a group of composite materials characterized by combining the desirable properties of residual metals: ductility and toughness with those of hard materials: high hardness and wear resistance. The term refers to traditional hard metals usually made of tungsten carbide with cobalt as the metal binder. There are, however, several hard metal systems, where other combinations of hard materials and metal binders have been developed and commercialized. Carbide-based composites are generally powdered metallurgical materials obtained by compaction and sintering in the presence of an appropriate catalyst that facilitates the densification process by liquid-phase sintering [13]. The fabrication process includes several steps that can significantly influence the material and performance of the final product. The mechanical and electrical properties are determined by the chemical composition of both the hard and the binding phases as well as by the microstructural features of the composite [14]. These features could include grain size, distribution and orientation of particles, the phase distribution, and the porosity (Table 2,3).

MANUFACTURING PROCESSES

In general terms, a refractory is a material that can withstand high temperatures. One considered refractory may not be so for another application. Depending on their application, different types of materials show different thermal performances. For example, a structural ceramic typically

used at room temperature would be considered a refractory material if used to construct parts for a manufacturing process like titanium casting, which operates at a temperature above 1600 °C [15]. The materials used in these applications are known as high-performance or high-temperature materials, and they are a concern for many different industries, including aerospace, oil and gas, and the metallurgical and ceramic industries, to name a few, which have manufacturing processes that reach temperatures above 1000 °C [15].

Alumina, silica, zirconia, as well as their blends, are some of the most used refractory materials. They can be used as bricks or grains for casting powders and are produced using a similar production process. The starting materials are primary oxides, easily obtained from naturally occurring minerals. With a series of steps that can vary from case to case, the production of the final products involves a preliminary preparation, such as crushing, milling and sieving, an agglomeration step, which usually includes the granulation of the powders and their calcination, and calcination at high temperatures to eliminate all the impurities, to obtain large purity precursors [16]. The purified powders are then shaped and lastly fired at temperatures above 1000 °C to make them solid. The refractory bricks are then assembled with other materials to formulate the final parts to be used in manufacturing processes below their melting point, typically conducting only thermal shocks or mechanical stresses, while the grains for casting are used as they were

Table 4A. Comparative table summarizing properties

Category	Traditional refractories	Advanced refractories
Composition	Alumina, silica, fireclay, magnesia	Nano-ceramics, composites, carbon nanotube-reinforced, geopolymers
Thermal resistance	Good (up to ~1700°C)	Excellent (>1800°C), with enhanced thermal stability
Mechanical strength	Moderate	High (nano-structuring & reinforced matrix)
Thermal shock resistance	Poor to moderate	Very high (e.g., nano-composites)
Corrosion resistance	Limited in acidic/basic environments	High resistance to slag, acid, alkali, and molten metals
Lifespan/durability	Short to moderate (months to 1-2 years)	Long lifespan (multi-year under heavy use)
Ease of fabrication	Simple shapes, casting or pressing	Custom shapes via 3D printing, robotic precision

Table 4B. Applications table

Industry	Traditional refractories use	Advanced refractories use
Steel & Metallurgy	Furnace linings, ladles, kilns	Smart linings, wear-resistant nozzles, predictive maintenance tools
Cement	Rotary kiln linings	High-resilience nano-lined walls with thermal feedback
Glass	Melting tanks, regenerators	Erosion-resistant, energy-saving smart linings
Petrochemical	Reformers, crackers	High-temperature sensors, corrosion-resistant linings
Power Generation	Boilers, incinerators	Self-healing linings, enhanced thermal cycling materials
Aerospace	Rarely used	Heat shields, jet engine components, thermal barrier coatings
Electronics/semiconductors	Not applicable or very limited	Precision sintering chambers, ultra-pure ceramic linings
Waste-to-Energy	Linings exposed to corrosive waste gases	Durable, eco-friendly materials that resist chemical degradation
Industry	Traditional Refractories Use	Advanced Refractories Use
Steel & Metallurgy	Furnace linings, ladles, kilns	Smart linings, wear-resistant nozzles, predictive maintenance tools
Cement	Rotary kiln linings	High-resilience nano-lined walls with thermal feedback

Table 5. Limitations of traditional vs. advanced refractory materials

Aspect	Traditional refractories	Advanced refractories
Performance degradation	Rapid wear under cycling & chemical attack	Minimal, but sensitive to fabrication accuracy
Customization	Low – standard shapes/sizes	High, but requires digital manufacturing tools
Monitoring and maintenance	Manual inspections only	Requires IoT/AI infrastructure
Initial investment	Low	High (material & digital system cost)
Recyclability	Poor	Good, but needs specialized recycling processes
Availability	Widely available	Limited to specialized suppliers

fired, therefore withstanding the melting and high thermal shock from the injection of a molten metal (Table 4,5).

It is well known that many refractory materials, especially the aluminas and silica, usually demonstrate an improvement in thermal performance when this processing route is altered, enhancing further agglomeration and granulation processes and minimizing firing steps. After pointing out how a refractory material is characterized, the affinity of these materials for this particular type of processing route is reviewed [17]. The main but few modifications

to the traditional processes used to reduce their porosity and increase their shape retention during high temperature firing are summarized. Lastly, hot isostatic pressing, gel casting, and other types of casting processes that produce well-defined shapes end by them directly after a single firing step are described [18].

Precision Manufacturing Techniques

Precision manufacturing techniques are the methods and processes utilized in the fabrication of high-performance components in a wide variety of industrial sectors.

Generally speaking, the objective of these techniques is the production of components with exceptionally tight dimensional tolerances. However, the term “precision manufacturing technique” may incorporate several aspects, from grinding and lapping to the employment of some emerging technologies such as ultra-precision micro-milling, micro-electrical discharge machining, or high-precision three-dimensional printing. The impact of specification technologies is increasing in a rapid fashion because of their special capabilities. Work pieces produced by these technologies have precision and dimensional capabilities on the nanometer scale and are increasingly being regarded as viable alternatives for use in ultra-precision manufacturing applications [19]. However, the competition for such applications remains very tight and globally competitive, as traditional techniques such as ultra-precision diamond turning, ultra-precision grinding, and boring hold many advantages for processing components with very special cross-sections.

Additive manufacturing generally refers to the use of computer-controlled techniques to create a three-dimensional object by adding material layer by layer. This term encompasses a variety of processes that have in common the use of computer control and the incremental addition of material – typically through liquid, powder or sheet material – to build up desired part geometry [20]. Basic processes for additive manufacturing include material extrusion, vat photopolymerization, bind jetting, material jetting, powder bed fusion, sheet lamination, and direct energy deposition. These techniques can handle a variety of thermoplastic and thermoset polymers, metals, glass, and ceramics. One of the most attractive advantages of additive manufacturing is the design freedom, eliminating the requirement of part manufacturability. Parts with internal structures such as lattice structures or with complex geometries can be designed and fabricated in additive manufacturing without additional cost or effort. Additive manufacturing is touted to be a revolutionary technology that holds promise for applications in a broad range of industrial sectors including aerospace components, biomedical implants, automotive parts, and jewelry [21].

Casting and molding techniques are two of the most important processes in contemporary material forming technology. Atmospheric pressure casting is widely used in many industries for the production of complex shapes and is one of the oldest processes associated with metal. Casting processes encompass continuous casting; die casting, investment casting, lost foam casting, sand casting, ceramic shell casting, tilt pouring, squeeze casting, co-bulation, and centrifugal casting [22]. Molding processes include plastic injection molding, metal injection molding, rubber injection molding, sheet molding, resin transfer molding, vacuum-assisted resin transfer molding, and precision gravity molding. Molding processes involve the shaping of material using molds with the application of heat and/or pressure. Most molding processes are batch processes.

intelligent Kilns for Ceramic Manufacturing (Industry 4.0 Pilot in Germany): A ceramics manufacturer in Germany experienced inconsistencies in kiln temperature distribution, leading to uneven product quality and excess energy consumption. They upgraded to intelligent kilns with:

- Smart bricks (refractory materials embedded with micro-sensors).
- A network of IoT devices inside the kiln to track heat distribution, gas flow, and structural stress.
- Cloud-based analytics to control airflow and burner patterns dynamically.
- 15% improvement in fuel efficiency.
- Product rejection rate dropped by over 20%.
- Enhanced reproducibility and uniform heating cycles.

Embedding intelligence into kilns transforms them from passive heat chambers into self-regulating, adaptive systems that ensure product quality and energy optimization.

Additive Manufacturing

Additive manufacturing (AM), also known as 3D printing, has emerged as a revolutionary fabrication technique capable of transforming complex computer-aided design (CAD) models into physical objects with unprecedented geometric complexity [10]. The evolution of different additive manufacturing techniques, particularly desktop-sized and large-feature additive manufacturing systems, has opened up novel avenues for the next generation of refractory materials, specifically engineered for diverse high-temperature applications. With increased autonomy and reduced costs, refined techniques for composite feedstock formulations, as well as sinterable and fully meltable constituent materials, have streamlined the incorporation of a diverse array of thermoplastic polymers and inorganic precursors for passively joined material systems.

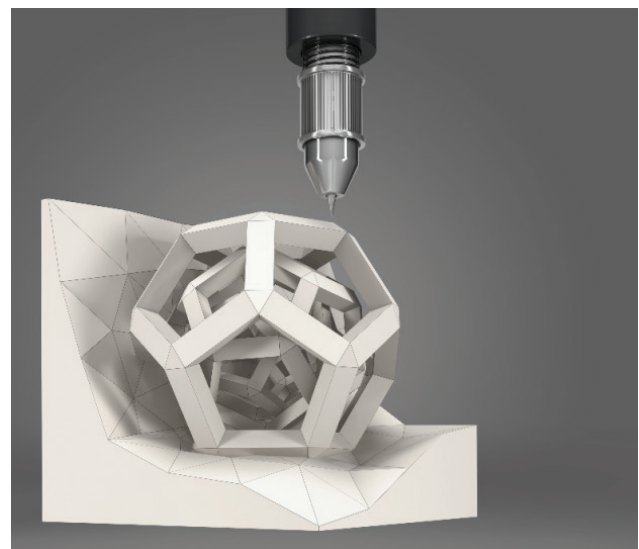


Figure 1. 3D printing methods and future trends for advanced ceramics 3D printing. [Adapted from Nanoscribe GmbH].

Generally, the term “additive manufacturing” refers to a family of techniques capable of processing materials deposited progressively—layer by layer—into a desired three-dimensional (3D) topology. In essence, additive manufactured semi-finished products or finished parts consist of intricately three-dimensional material architectures, often characterized by varying material compositions or microstructural arrangements in defined regions of the object, herein referred to as 3D material systems. As a subclass of aggregate additive manufacturing techniques, material systems printing can be classified as either “binder-free” printing, where dry granular material (powder) is essentially fused by subsequent processing stages, or as “modified” printing, where 3D material systems composed of mixtures of constitutive serial inlet tapes or filament and additional binder or filler components can be inscribed (Fig. 1) [23].

The object topology to be printed is defined by a computer-aided design (CAD) file that is subsequently sliced into 2D cross-sections for generating respective digital path files to be imparted to the additive manufacturing system. The topology definition and CAD model processing stages are generally referred to as a “pre-processing” suite. Subsequently, the digital path files are interpreted within the additive manufacturing system and the printing itself is performed in a series of pro-active steps. This suite usually comprises mechanical and/or thermal material processing and forming steps apt for progressively depositing the digital cross-section layer by layer in the material building section corresponding to the additive manufacturing equipment’s resolution. The additive manufacturing process steps used to build a part are commonly described as a “processing” stage or “main processing” suite. Finally, the as-printed objects typically exhibit

size, resolution and/or geometrical inaccuracies due to the respective layer thickness, sloping angles or thermally endogenous effects. Such defects can usually be counteracted by means of further “post-processing” steps comprising traditionally either thermal processing (de-binding and sintering) or machining/filing [17].

CASTING AND MOLDING TECHNIQUES

Casting and molding techniques are versatile precision manufacturing methods that can produce complex, high-accuracy geometries in highly refractory materials—some of which cannot be easily achieved by conventional metal fabrication processes. This section summarizes stereolithography, binders and slurry formulations, and casting and molding applications with an emphasis on refractory ceramics.

Stereolithography (SLA) is an additive manufacturing process that uses a focused ultraviolet laser light beam to polymerize a biocompatible resin in a layer-by-layer manner. SLA can achieve a resolution higher than 100 μm , which is significantly smaller than the typical resolution of powder-based binder-assisted additive manufacturing processes ($> 200 \mu\text{m}$). SLA-based stereolithography ceramic manufacturing has been explored as a novel method to fabricate ceramic scaffolds in biomedical applications. SLA technology has also been adopted to shape highly dense ceramics for structural applications.

Casting and molding typically involve shaping refractories compounded with polymeric and ceramic powders via slurry formulations. This section introduces a few common types of molding, including slip casting, tape casting, and gel casting. Casting and molding applications

Table 6. Subsequently densified, all steps being well-established traditional ceramic processing

Step	Description	Purpose	Tools / Sources used
1. Literature review	Survey of academic papers, industry reports, and patents	Identify current advancements and research gaps	Scopus, ScienceDirect, IEEE Xplore, Google Scholar
2. Comparative analysis	Compared traditional vs modern refractory materials and manufacturing methods	Evaluate improvements in performance, cost, and sustainability	Data tables, performance metrics, case data
3. Case studies	Real-world examples from aerospace, steel, and cement industries	Assess practical applications of digital technologies	Industry reports, journal articles, technical whitepapers
4. Technology integration mapping	Correlate digital technologies with specific manufacturing and material functions	Understand synergies between smart tech and material science	Mapping matrix, CAD/CAM documentation
5. Expert consultation	(Optional) Interviews or surveys with researchers and engineers	Gain industry insight and validate findings	Email interviews, questionnaires
6. Synthesis & recommendations	Consolidate insights and propose future directions	Provide actionable conclusions and suggest future research or applications	SWOT analysis, summary charts

in the preparation of ceramic scaffolds for bioreactors, as well as freeze casting for thermal barrier application, are summarized.

Casting and molding techniques utilize molding structures made of polymeric materials or metals/traditional ceramics that form and define the geometries of the fabricated parts. Particles are added to liquid forming compound slurry, which is then dispensed onto a mold and allowed to dry. Casting and molding techniques are versatile and can produce complex geometries unattainable via conventional metal fabrication processes or even other highly refractory manufacturing techniques (such as die pressing). Another advantage of casting and molding techniques is the ability to fabricate large numbers of identical ceramic components. Upon drying, green parts can be handled, debinded, and subsequently densified, all steps being well-established traditional ceramic processing.

To produce defect-free components, slurry formulations use weight ratios of solid loadings, dispersants, binders, and pore formers depending on the chosen molding or casting technique. Co- and tri-axial molding techniques are combined with additive manufacturing to fabricate ceramic, polymeric, and metal parts of various materials properties that cannot be attained by either technique alone (Table 6).

Synergistic Applications of Refractory Materials and Precision Manufacturing

The field of precision manufacturing has achieved remarkable advances over the past 20 years that have improved geometric controls on dimensionality and surface characteristics unmatched by other types of processing technologies. Insights gained from these achievements have led to a new frontier of endeavors that seek revolutionary approaches to near-net shape processing of low-cost and hard-to-image materials that could fundamentally change the manufacturing paradigm for these materials. Figure 2 focuses on marginally established technologies that are especially relevant to the near-net shape processing of ceramics or ceramic-reinforced composites, along with reliably established technologies like advanced ceramic processing.

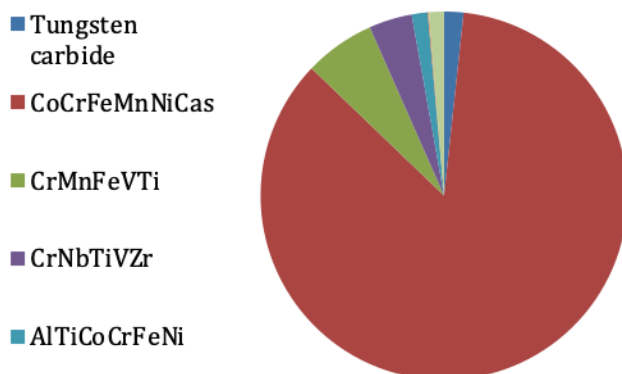


Figure 2. Hardness (HV) for type of alloy.

Despite all of the above advances, there still exists a need to fundamentally change the manufacturing paradigm for hard brittle-to-stiff materials (ceramic and ceramic-reinforced composite materials) from subtractive processing toward additive or near-net shape processing technologies. Additive processing technologies are either impractical or not cost-competitive for low-cost, brittle-to-hard materials. On the other hand, established advanced shape processing technologies (e.g. Isotropic Sintering Process) mostly have limits in terms of what initial shapes can be processed and are restricted to small parts. Further, only complex 3D shapes can be manufactured soundly by isostatically pressed polymer-bonded green parts, while for simple plane shapes, either solid or hollow (tubular), the casting method is normally chosen, which brings a lot of old disadvantages trying to fix. On top of that, sand-cast alumina at the current foundry technology level cannot be economically competitive due to exceedingly high fixed costs.

Thus, it would be a big leap to fill the processing gap and to introduce entirely new near-net shape processing technologies especially dedicated to the processing of rigid-to-brittle (ceramic and ceramic-reinforced composite) materials. This processing gap challenges the manufacturability of desired products by this type of difficult-to-process materials. There are various applications for low-cost ceramic tile materials, such as thermal barriers, scrubbing pipes, wear liners, wire guides, wedge holders for diamond wires, insulating tubes for laboratory systems for high temperature - high pressure experiments.

High-Temperature Applications in Aerospace Industry

Refractory materials and precision manufacturing techniques are of paramount importance in high-temperature applications within the aerospace industry. Notably, jet engines, turbo machinery, and aerospace components experience some of the harshest operating environments, which impose requirements on materials, parts, and their processing that are not needed in lower temperature applications. Currently, this need is serviced with high-performance materials like superalloys and high-temperature composites, which have effectively reached performance limits in some applications. Innovative advanced ceramic materials in conjunction with new precision manufacturing processes are the building blocks that will enable unlocking solutions to impossibly difficult high-temperature aerospace problems.

Modern aerospace engines, both turbojet and turbofan, expose hot section combustion components like nozzle and turbine blades to some of the harshest operating environments in the world. Figure 3 investigated effect operating temperatures at the blade tip are sometimes greater than 1800°C, nearly 300°C in excess of the melting point of the superalloys used for this airfoil. In order to withstand such extreme environments, these blades are often subjected to advanced cooling techniques that often involve complicated fine scale internal conformal cooling passages within

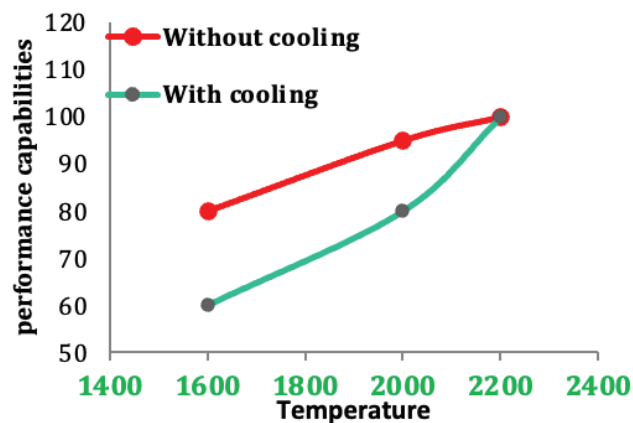


Figure 3. Effect of temperature on jet engines and turbines components.

the part. State-of-the-art technology for the manufacture of such high-performance airfoils is investment casting, which is inherently poor at achieving small enough feature size and scaling capability to create the complex cooling passages needed to fully exploit the performance capabilities of the latest state-of-the-art superalloys. For these reasons, there exists a technological need to develop precision manufacturing processes capable of fabricating complex shapes in superalloys and refractory materials that cannot be fulfilled by traditional casting or machining technologies.

Advances in ceramics and ceramic-matrix composites (CMCs) have placed a new class of high-temperature materials at the forefront of both architectural and thermal protection system components for both aircraft and spacecraft. The need for greater engine efficiency and increased vehicle maneuverability has encouraged interest in CMC nose cones and thermal protection system components, as well as ablating-material nozzles and domes. Current craft use invasive ablators that gradually erode away during re-entry, heating water a few hundred degrees. New designs utilize rigid materials like CMCs that can survive entry temperatures of thousands of degrees while keeping the innermost layers below the threshold for structural failure. CMC composites have an additional weight advantage compared to metal-alloy architecture for airframes and wing skins in reusability applications. However, up to the present, challenges in the attainment of repetitively manufacturable structures and hulls have stymied deployment. A critical need exists to attain repetitive structures for application in both Earth-return craft and military vehicles.

Jet Engines and Turbines

With the expanding commercial flight market, there is an increase in demand for both efficiency and performance of jet engines and turbines. An increase in pressure ratio allows the engine to operate at a higher temperature for greater efficiency. Nevertheless, given that the turbine materials are subjected to extremely high pressures (30-50x

atmospheric pressure) and high temperatures (1500-2000 °C), there is a limit to an increase in temperature. A combination of a more efficient cooling system and blade design would increase the efficiency further. However, there is a reduction in robustness and increase in complexity. Evidently, there is a requirement for robust, high-temperature resistant materials during failures of jet engines.

Due to the complex operational environment, jet engines and turbines require innovative alloys and materials with specialized properties. Jet engines operate in a temperature environment that can reach up to 700 °C while turbines can go significantly higher, pushing 2000 °C. Operating at high temperatures increases the efficiency of the engines and turbines; however, as temperature goes high, there is an increase in wear, thermal cycling stress and fatigue stress; all of which cause cracks and eventually catastrophic failure. Hence the material must exhibit a very high melting point, high thermal shock resistance, low thermal expansion, low temperature gradient internal stress, and a low thermal stress coefficient. The materials must be able to resist corrosion from oxidation and liquid metal due to the interaction with very hot air, supercritical CO₂, or molten metal alloys in nuclear reactors. Natural ceramics, i.e. quartz, clay, bauxite, etc., exposed to solid and gaseous oxidizers become sintered oxides at a temperature of 1000-1300 °C. Natural ceramics can also be sintered at 800 °C in supercritical CO₂. Hence refractories, jetted ceramics, and cement based on natural raw materials exhibit, in most cases, the necessary insulating properties and can sustain corrosion from molten sodium.

Spacecraft Components

Spacecraft components represent another important area of high-temperature applications in the aerospace industry, which requires materials that can withstand extreme thermal stress and endure high temperatures. Several spacecraft components such as thermal protection shields and nose tips require heat-resistant materials. Refractory materials like ZrO₂/TiO₂-based ceramic blended with polymers, UHTCs, and composites, working either in rigid systems or ablative configurations, are widely used for the thermal protection of spacecraft components. Reusability of these components is highly desirable because of the extremely high cost of launching satellites into low Earth orbit and high Earth orbit. Re-entry materials must withstand high heating rates (>200 °C/s) and require high thermal inertia, low thermal conductivity, and moderate specific heat capacity. Because of the inflight aero thermal ablation of ceramics (Fig. 4), the space shuttle used lower temperature resistant materials like silica.

Since the proposals for the space shuttle, a new and higher temperature resistant candidate, ultra-high temperature ceramics (UHTCs), fused to composite structures for nose tips and leading edges, have been presented. These ceramics can withstand 2200 °C and provide ablation and insulation if the density of the composite is kept low (<55%

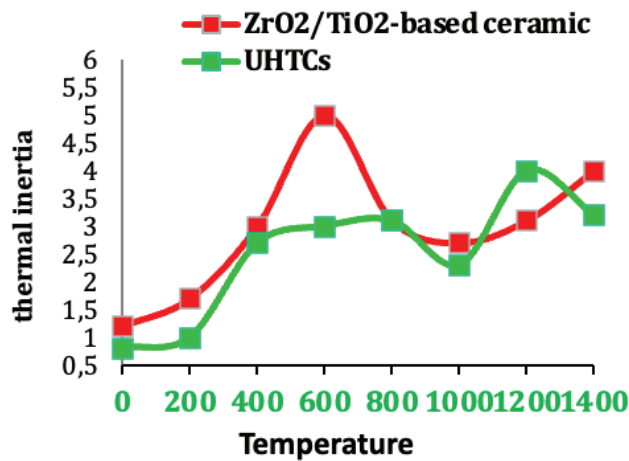


Figure 4. Thermal inertia for two components.

of that of silica) but still withstands 1-1.5 kC of heating. The presence of carbon or de-pyrolised polymers in the composite is necessary to form a protective char layer. With more flexible thermal protection, the Global Positioning Satellite (GPS) system may be adopted for flight, descent, and satellite tracking.

In recent years, several spacecraft return missions from various celestial objects have been attempted. So far five spacecraft missions have returned from four different celestial objects (a comet, asteroids 25143 Itokawa, 162173 Ryugu, and the Moon) and brought back samples for analysis. The entry of these return capsules into the atmosphere requires the samples to undergo severe heating to >700 °C, which is typically done with quartz-based silicas that melt and ablate. Since quartz is incompatible with NASA’s Curiosity rover’s high-temperature instruments, ZrO₂/

TiO₂-based ceramics blended with polymers for ablation resistance have been developed, which can return from high LEO orbits in a dry, non-aggressive environment without melting or disturbing the sample.

High-Temperature Applications in Energy Sector

High-temperature applications are typically found in turbomachinery parts like blades and combustion chambers. After gas limestone calcination, of late interest in the present global scenario are carbon dioxide confinement, but also mineralization and valorization for use in concrete as a more sustainable building material. High-temperature resistance for precision components associated with ten years of progressive investment with stringent multi-level target inclusions, processing, and performance monitoring made fine-tuning achievable through enhanced manufacturing efficiency, cost reductions to the lowest industrial-level processing, and devoted property tracking. Advanced via edgeless design, EPT loss mitigation extends microstructural integrity and homogeneity suited for canals and passageways. Considering reduced geometries in paraboloid methodology for laser systems, two recent applications are outlined. Gas turbines constitute the most efficient power plants for natural gas, switching to hydrogen, syngas, or net zero carbon units, enhancing material demands. Precision manufacturing techniques are available in power generation domains. Some R&D examples comprise combined vapor-water cladding, constrained growth and pre-matched ranges for low distortion fabrication, and layered casting for sintering actions enhancement (Table 7).

The latter has process monitoring techniques free to development. Regarding combustion chambers and blades, precise design geometries featuring canals are driven to manufacturability. Considering rising computational fluid dynamics efficiency with free software availability,

Table 7. Applications of spacecraft components

Category	Advancement	Applications
Refractory material design	Nano-engineered ceramics, advanced composites	Furnaces, kilns, aerospace heat shields
Additive manufacturing	3D printing of refractory parts using ceramic slurries or powders	Custom refractory linings, prototypes
AI & Simulation	AI-based material modeling, digital twin for heat prediction	Optimizing furnace designs, reducing energy loss
Precision machining	CNC machining of ultra-hard refractory materials	Aerospace, defense, high-temperature tooling
Smart monitoring	IoT-enabled refractory monitoring systems	Steel, glass, and cement industries
Coating technologies	Plasma spraying, laser cladding of refractory layers	Turbine blades, rocket engines
Sustainability focus	Use of recycled refractories, eco-friendly binders	Metallurgy, cement production
Digital quality control	Automated inspection using machine vision and sensors	Refractory brick production, part validation
Custom alloys & Binders	Advanced binder chemistries, high-performance metal-ceramic systems	Foundry molds, induction furnaces

methodological addressing to hybrid generate-apparatus files, EPT safeguarding tight tolerances handling lost wax castings, or investment molds have been giving new avenues for proposals. Coupling blade numerical design and smart traversal simulation paths enabling EPT resolution tracking and graphite gains controlling geometries make the design conversion into solid-modelling creation or stereolithography files less challenging. Similar considerations apply to centrifugal blades. On-site finishing machining remains for last-resort means.

The recent return of high-nickel alloys coating consideration opposes CRTM open ingenuity enhancement tempo for insatiable, nitride-free demands added at dusk generic specifications. As a technical dwindle internationally, investments yielding patent submissions free to lease become contesting avenues for immediate review. Stay aware; maintain competitive with explosion brakes and wood-like fuel processing systems sprinkling overseas investments.

Gas Turbines and Power Plants

Gas turbines are used in combined cycle power plants to produce electric power from natural gas, diesel fuel, and more recently, biofuels. In many countries, combined cycle power plants are the favored way to produce electricity because they are the most economical cycle. The electric power for turbojet aircraft and turboprop aircraft is provided by gas turbines. The gas turbine aircraft engine is basically a gas turbine adapted for aircraft use and is known as a jet engine. In addition to serving on aircraft, jet engines also power helicopters. They can also provide thrust on naval surface vessels and submarines. Jet engines are also installed in rockets.

Gas turbines used in aero engines are usually of the high bypass type; this means that a lot of air passes around the engine core. A special type of high-bypass engine is called a fanjet. Gas turbines used in stationary plants may be either of the high- or low-bypass type. In a commercial gas turbine engine, air is taken in at the front. The fan compresses most of the air and passes it to the core. A small amount of air goes into the core bypass. The pressure increases as the air passes through the compressors. The increase is about 12 times in a subsonic engine and 30 times in a supersonic engine before it enters the combustor. The primary flow goes through the combustor where air is heated by burning fuel. The fuel is injected into the air by fuel nozzles. The combustion takes place in different zones in the combustor. The flame is stabilized by flame holders which produce turbulence. The high-pressure, high-velocity gas produced in the combustor expands through the turbine. The turbine extracts some energy from the gas to drive the compressors. The remaining energy drives the jet nozzle and produces thrust.

Nuclear Reactors

Nuclear energy is one of the leading carbon-free energy generation technologies, storing more than 10% of global

electricity generation and contributing more than 25% in decade-long developed countries. The nuclear power generation system can be profoundly classified into thermal reactors and fast reactors based predominantly on the neutron energy group related to the core fission chain reactions.

Thermal reactors use low-enriched uranium fuel and activate thermalized neutrons (0.025 eV) for fission reactions, contributing approximately 75% of worldwide commercial nuclear electricity generation. To achieve effective thermalization, the core is commonly moderated using graphite, high-purity water, or lattice cell configurations equipped with chemical substances such as boron and gadolinium.

Fast reactors, on the other hand, use high-enriched uranium-composed or mixed-oxide (MOX) plutonium-based fuels and implement strictly fast fission chain reactions using insufficient low-moderated core or no-moderated core configurations. Structural and thermal-hydraulic materials of nuclear reactors, upon decades of installed application experiences, have been found beneficial to syndicate composite manufacturing or additive manufacturing solutions.

Nuclear criticality safety systems (CSSs) using boron-based, lithium-based, or hafnium-based against various reactions of thermalized n-traps (nH, nB, nLi) and fast capture reaction (nHf) have been multi-decades applied with outstanding operating performance. Nevertheless, the utilization of these promising materials as new composite nuclear reactor core materials is virgin and needs in-depth studies to thoroughly evaluate their application in nuclear reactor design and assembly.

With the deep decoupling of concentrations between series of thermal core traps and fission minerals such as Water-Cooled Polymer (WCP), thermal n-capture cross-section less than boron/B₂O₃ has been proven computationally, fabricating synthesizing or additive manufacturing of complex graphite/boron, polymer/metal expanded structures, and monolithic targeted decoupling minigrain compositions composite configurations feasible in thermal reactors.

The uniqueness of nuclear reactors is to utilize nuclear fission generated ten millions-prodigy thermal energies and transmute the heat into industrial standards in megawatt amplified. The preliminary thermal energy techniques are to boil water to launch high-speed steam systems on turbines and continuously to circulate condensed water as a working fluid to passage through heat-exchange piping systems. Conventionally, this has been considered the current thermodynamic cycle.

However, the descending duration of similar exhaust thermal energies to the environment has resulted in heats concentration and limitations to heavily supplied electric-drawing industrial equipment. Therefore, novel thermal energy standards generate more than several hundred-degree centigrades of thermodynamic working fluids to directly drive industrial type turbines, such as using gas

CO₂ to drive gas turbines, or the synthesis of molten salts to apply directly on the thermal-GT-nuclear power system. Thus, non-electric applications on ship propelled mining could be chiefly.

High-Temperature Applications in Automotive Industry

As global environmental regulations and customer demands become increasingly stringent, engines are being subjected to ever greater stresses. Figure 5 presents how innovative composite materials can contribute to lightweight design and heat protection in engine components and exhaust systems. Carbon-fiber-reinforced polymers (CFRP) are becoming a viable option for replacing metals in automotive and aerospace applications due to their high strength-to-weight ratio and high temperature capability. However, there are critical challenges for CFRP to be considered for high-temperature exhaust applications. An overview of internally developed high-temperature polymer systems under consideration for automotive applications is given along with manufacturing requirements and first machine part examples.

In densely populated urban areas, cleaner exhaust gas emissions are needed to reduce particulate emissions that can affect public health. On the other hand, stricter regulatory targets with a double CO₂ reduction target within the next decade put pressure on both combustion and non-combustion engine engineers to keep innovating for cleaner and more efficient engines. Synergetic with exhaust emission developments, automotive mechanical issues such as robust engine designs, cost saving, and weight reduction challenges have to be met. For cost-efficient metal technologies, there are limits that cannot be exceeded in automotive-grade materials such as aluminum (Al) and iron (Fe) – which are widely used in pressure vessels, oil sumps, turbo housings, smoke exhaust pipes, pneumatic turbo returns, etc. Polymer materials are favored over metals by

better functionalization options from properties other than essential OEM requirements such as sealing.

Unlike traditional studies focusing purely on material composition, this work explores how AI, machine learning, and digital twins are being used to predict, model, and optimize refractory performance, enabling faster innovation cycles. While earlier research has covered ceramic printing or general additive manufacturing, this work highlights application-specific 3D printing of refractory materials, particularly in high-temperature industrial settings, offering tailored geometries and on-demand production. The integration of IoT sensors and real-time monitoring systems into refractory-lined equipment is a recent advancement that shifts the paradigm from reactive to predictive maintenance, which previous literature has not fully explored. The work brings in eco-conscious innovations, such as the reuse of refractory materials and digital optimization to reduce energy use, creating a bridge between precision, performance, and environmental responsibility—an angle that is often neglected in earlier studies. This research highlights how aerospace and semiconductor-level precision is now being translated into heavy industries like metallurgy and cement through digital manufacturing techniques, which is a forward-looking perspective.

Composite materials with high temperature capability consist of polyimide and phenolic polymers as matrices, with reinforcement fibers made of carbon and aromatic PA. There are initial successful preprocess development milestones with out-of-autoclave prepregs and prepreg trays for preforming and pre-drying prepregs, as well as autoclave molds. CFRP high-temperature exhaust gas pipes also demonstrate superior behavior to temperature-resistant metallic exhaust pipes (457 and 309 stainless-steel pipes). Turbocharger inlet mass flows simulate vibration stress on the pipe. Boost pressure, weight, and cost figures are given for CFRP alternatives.

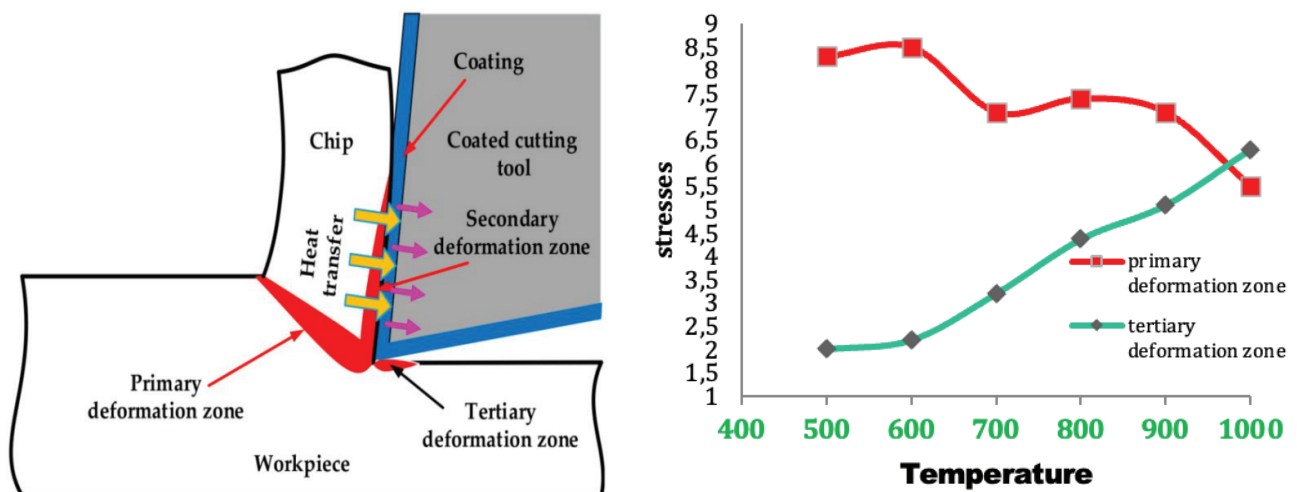


Figure 5. Stresses of carbon-fiber-reinforced polymers (CFRP) with different value of temperature.

With over two decades of experience in fiber-reinforcement composites, norms, sectors of the automotive and aerospace industry, continuous advancements towards the production of high-temperature composite parts and components of exhaust systems and turbochargers have been developed. These high-temperature composite materials consist of polyimide and phenolic polymers and can be reinforced with fibers of either carbon or aromatic PA. Key product development milestones achieved include initial successful developments of materials, process, and manufacturing methods to tackle problems associated with the traditional development process of high-temperature composite parts and components. Some of these known challenges include expensive and time-consuming processes due to very lengthy autoclave curing cycles and vulnerable bi-stability (preforming prepreg precisely according to design parameters).

Exhaust Systems and Turbochargers

Exhaust gas turbine housings (hot-side turbochargers) made from thin-walled castings are demanding applications for high-performance steel grades. High-temperature stresses and oxide scale growth affect their performance and durability. Depending on design and fabrication, different load conditions arise that cause failure by different mechanisms. Ultra-fine-grained (UFG) materials produced by severe plastic deformation (SPD) show promise in fatigue-critical applications. Multi-stage SPD processing can result in significant grain refinement while maintaining large-scale workpieces.

Cars with combustion engines, even hybrid ones, require turbochargers (TC) to guarantee enough charge air mass flow for good combustion. This requirement leads to high exhaust speeds and high wall temperatures at hot-side turbocharger castings, leading to thermo-mechanically highly stressed components. Good durability can be achieved with the state-of-the-art casting material for hot-side TCs, hereafter referred to as V3A steel. Nevertheless, policy regulations force automobile manufacturers to reduce vehicle CO₂ emissions, which results in bad durability of certain engine designs. This, in turn, is advantageous for novel, more cost-efficient, or more highly loaded TC designs, which need more sophisticated materials. The pure cast material V5A, for example, has no chance at all against classical higher alloyed grades. To understand whether this and more sophisticated pure cast steels can be used in high-performance TC applications, it should be considered how the TC casting does “see” the load and how it is affected by design, casting process, and post-casting process. Typically, TCs experience local thermal post-casting processes, which can result in a high level of thermal residual stresses that depend on the casting geometry and the thermal processes themselves.

Using the V3A and V4A cast steels, different cooling types for three different cast geometries with varying wall thicknesses were designed and manufactured. The temperature field and the thermal stresses in the castings during cooling were calculated using the Finite Element Method

(FEM). Thermo-mechanical simulations were then carried out for the designs with the biggest differences in material properties. This was done to gain a better understanding of the failure mechanisms in exhaust-side castings as well as to show ways to enhance their durability with ever-stronger materials. It was shown which material and design would be more favorable for improving durability in extreme driving conditions, grossly explaining the occurring load cases from a numerical view. Furthermore, using the V5A cast steel, lifetime curves of TC castings with different designs and load conditions were predicted using the temperature histories as input. Models for probabilistic lifetime assessment were established since, in case of larger fleets, the knowledge of the distribution of lifetimes of a component is of great interest.

Engine Components

One of the most important components in an engine is the cylinder head, as this piece closes off the cylinders and holds the intake/exhaust valves, spark plugs, and fuel injectors. The most important considerations for the cylinder head are: materials need to be able to withstand the temperature, corrosion, and wear properties of the engine fluids and gases, as well as mechanical stresses such as pressure and pyro-shock. Materials need to be mined/labor-intensive, and their prices fluctuate a lot globally. Manufacturability is very important, as complex designs require expensive machinery. Performance, as in maximizing the power output, increases return on investment. Different engine types have different head designs. Engine head materials are usually made out of aluminum alloys or cast-iron materials, both of which have their advantages and drawbacks. Common aluminum alloys include A356, A319, A383, and A518. Cast iron is heavier, cheaper and easily machinable, hence there is a wide variety of cast iron choices. There are also hybrid engine heads that utilize multiple materials, such as aluminum and iron, to weld bimetal heads, making it possible to use the advantages of the materials while masking their disadvantages. As for head manufacturing processes, most are made out of sand-casting: a low-cost and simple process that creates an accurate part. More advanced processes such as DSG, investment casting or squeeze casting are also applicable for these components. After initial processing, components undergo different coating treatments, such as nitro carburizing, depending on the engine type.

Another core engine component is the cylinder liner. A cylinder liner is the surface of which the piston is in contact with, and provides structural support to the piston, reducing the overall component count and facilitating part manufacturing. 55% of cylinder liners are made with high silicon aluminum alloys (A319, A356) and have a variety of coatings applied, such as friction-reducing coating and thermal-barrier coating. Most engine liners are produced with sand-casting, but there are also investment casting, squeeze casting, bushing manufacturing, and wrought options available. Along with the most important properties of thermal conductivity, thermal expansion, elastic

modulus, density, or micro-hardness, the soft-bronze batch liner eliminates the need for piston post-processing.

Another component group is turbo-chargers, specifically the turbine housing and exhaust manifold. Titanium-aluminides are gaining traction thanks to a favorable heat-resistance / thermal-expansion index ratio, meaning that they can survive hotter environment without thermally-expanding. There are drawbacks that have to be taken into account however: higher raw material price, processing difficulty, only attractive for 400oC-800oC engines, and possible failure after extended sodium use. Other than titanium, other alternatives have to be sought after, such as the gyroid and cubic cell integral structures; this means that besides weight reduction with latticing, performance improvement potential is also possible. Turbo-chargers are most applicable for diesel engines, as they enhance performance, increase driveability, reduce fuel consumption, and decrease exhaust emissions. There is also an increasing trend in laying out gasoline-particle filters, with a promising opportunity for alloy and manufacturing development.

Challenges and Future Directions

As with many materials technologies, there remain serious challenges ahead regarding the increased understanding, utility of advances, and broader implementation of current and emerging high-temperature environments and additive, DI, and hybrid manufacturing processes. Two significant issues, thermal shock resistance and environmental ramifications, are examined below; there are important lessons for industrial partners and interdisciplinary and cross-university collaboration, especially as they relate to synergistic advances in the microstructure/material, design/emulator, mach/boundary, additive manufacturing process/structural, and application/service environment.

The thermal properties of materials for extreme environments must be understood and optimized, yet many available materials fail to account for strain rate and thermal shock/fatigue effects. With first principles understanding of high-temperature (621-1496 °C) thermal shock nozzle testing of coal, steel, and ceramic materials, and these species may prove valuable beyond small-scale prototyping for larger loads, cross-industry transferability through warpage gradient learning, and modeling constrained architecture/geometry exploration. The potential interactions/uses with neural networks for examining uncertain/uncharacterized shapes are of significant interest. With the wide breadth of existing materials as a function of porosity density, irregularity, crystalline structure, and extent, there remains an important opportunity for the largest performance potential. Additional consideration must be given to research, development, and integration time of these materials.

Generation of materials with virtually no environmental impact (including less toxicity and particulate generation) is increasingly important if not imperative to avoid potentially devastating regulations across multiple global industries. Noting that most global energy production is

still reliant on fossil fuels, including coal (and the shock-waves resulting from the warping/deterioration of piping infrastructure) and oil/natural gas (attributed to the 83/85 Gulf and Macondo MacCade Oil spills), ceramics have the unique ability to exploit a complex or even extreme service environment/architecture for guaranteed material safety to chemical/thermal/electrical/mechanical fatigue/strain as compared to metals' vulnerability to oxidation/corrosion failures. There remains the potential for these recent advances in low-cost, lemon-hued Xi cement and porosity-dominated flexural strength tailoring to be applied in industrial testing scenarios for fly ash utilization to generate bricks as beneficial reuse of this environmental concern.

The specifications for diameter and part growth of components for application in the energy industry (catalytic converters, pipes, etc.) exist across a continent, and development and modeling should be pursued within alternate materials, emulators, and architectures extensively to confirm/simulate cases of interest. It is of utmost importance to recognize and incorporate all multiple dimensions and processes of an operation upon first application and evolve more complex designs after intended operation and intended design-space range confirmation. The current social ecosystem consists of an integration of technologically dependent tasks reliant on interdependent task completion that must be optimized and self-stand-alone modified by each component independently.

Thermal Shock Resistance

Thermal shock resistance is a crucial property for refractory materials exposed to rapid temperature changes. The ability of a refractory to withstand thermal shocks is determined by its thermal expansion coefficient, thermal conductivity, and mechanical properties. Understanding the mechanisms of thermal shock damage is essential for predicting and preventing such damage in refractory linings.

Refractory bricks used in high-temperature, thermally shocked, and corrosive environments have been studied through a combination of three-point bending strength measurements, optical and scanning electron microscopy, and thermal shock testing. The thermal shocks were applied by cyclic heating in a high-temperature furnace, followed by quenching in water. The outbreak of damage was found to occur at a critical temperature gradient, which was estimated using the previously formulated criteria of thermal shock failure. The mechanism of thermal shock resistance variation was demonstrated to be due to the thermal shock activation of exothermic gelation/hardening reactions in the silica binder of refractory castables. The matrix continued to strengthen even after the bricks cooled down to room temperature, preventing the total collapse of the lining. The glass-like layer formed on the surface of bricks due to thermal shock-induced melting/sintering of matrix components slowed down the spalling process considerably.

Thermal shock resistance is a critical property for refractories employed in glass melting furnaces. Refractories are

often lined in furnaces subjected to instantly applied and heterogeneous heat loads, leading to steep temperature gradients. Gradients from hundreds of degrees Celsius in minutes may occur, exposing the lining to thermal stresses higher than its yield strength. Thermal shock damage in the lining, controlled by physical phenomena rather than thermal stresses, may be initiated even before temperature levels rise to the point of yielding. Important economic losses may arise from breakage and maintenance interventions, thus having good thermal shock resistance are of utmost importance for refractories.

Understanding the phenomena behind the thermal shock damage of a refractory material is essential for predicting, evaluating, and preventing such damages. The material composition and former history, lining geometry, operating conditions, and refractory lining cooling method are some criteria that define the thermal shock vulnerability. Therefore, reliable evaluation of pressing, casting, or sintering methods is crucial, and simulation of industrial conditions is strongly required. The processes themselves relevant to the ongoing research and development of novel silica-free low expansion castables are discussed.

Sustainability and Environmental Impact

The issue of sustainability and the environmental impact of raw materials used in the manufacture of advanced ceramic refractories have received limited attention, as evidenced by a review of published literature. Interest in the environment and sustainability has grown since the United Nations published its sustainable development goals (SDGs) in 2015. To increase awareness of its significance in the manufacture of ceramic refractories, the ecological impact of ceramic refractories should be quantified throughout their lifecycle, from the quarry to production

and final disposal. Further efforts should be made to engage organizations and stakeholders in technological and research fields connected to ceramics and materials so that the environmental impact of raw materials can be reduced. The environmental impact of ceramic refractories is currently relatively poorly assessed and quantified.

However, significant challenges can be found regarding the waste and recycling of ceramic refractories, along with the need for knowledge development in substitution of raw materials or industrial residuals in the manufacture of ceramic refractories. Until now, advanced ceramic refractories have been employed in low-end applications, as many material properties are related to the manufacturing process and the amount of energy needed for processing ceramic materials at high temperature. Unlike metals, high temperature ceramics are brittle and therefore require careful processing to avoid cracking and failures. The greatest technological effort in ceramic industries is expected to concern the development of near net shape manufacturing technologies and advanced refractory shaping, such as additive manufacturing and plasma-forming methods. Efforts should be oriented today to neutralize cracking in processing by co-designing the fabrication approach and the materials that are used for refractories in high temperature applications. Elaboration of the holistic design of advanced high temperature ceramic systems is challenging at the moment due to the complexity of the material properties that play a role in their final application. Specific example of digital transformation in manufacturing: Siemens’ digital factory for gas turbines (Table 8).

Company: Siemens , Application: Gas turbine blade manufacturing , Location: Berlin, Germany (also applied in other global facilities) And Initiative Launched: Ongoing since ~2016

Table 8. Applications of company: Siemens

Technology	Application
Digital twin	Virtual model of the entire turbine blade production line for simulation & optimization.
Additive manufacturing	3D printing of intricate cooling channels inside turbine blades using metal powders.
IoT sensors	Embedded in machines to monitor temperature, vibration, and real-time process data.
AI and machine learning	Optimizing tool wear, predictive maintenance, and defect detection in real time.
Cloud computing	All production data stored and analyzed across systems for global collaboration.

Table 9. Benefits and results

Metric	Before digitalization	After digitalization
Production time (per part)	~16 weeks	Reduced to ~6–8 weeks
Error rate/Defect detection	Manual inspection	AI-enabled vision reduces human error
Design-to-production time	Long cycle (months)	Digital twin allows rapid prototyping
Customization	Limited	Mass customization with 3D printing
Maintenance	Reactive	Predictive maintenance via IoT + AI

Siemens also applies digital twin simulation to test heat distribution and wear on refractory linings inside the turbine casting molds. This allows for:

- Better refractory design
- Faster failure prediction
- Reduced material waste

Untamed challenges concern the design of tailor-made properties in an interdisciplinary methodological way from the processing and shaping to the use of the final product. Some of the technological areas needed to reach the challenging demands on advanced ceramics will concern, e.g., low invasive processing and reduction of process-induced stresses such as cracking in manufacturing, environment friendly dry shaping and sintering approaches, refinement of properties on large components in changed design/construction-oriented technologies for ceramics and composites (Table 9).

CONCLUSION

Advances in refractory materials and precision manufacturing techniques for high-temperature applications, such as thermal protection systems, crucibles, and molds for metal casting, represent the integration and synergy of these two topics on three levels. The first level is the new composition of the material, which is an improvement to existing materials, advances in compositions, and classes of new materials. Without refractory materials, most high-temperature industrial processes would be unsafe, inefficient, and uneconomical. They are invisible yet essential components that protect both equipment and people, while enabling the innovation and sustainability goals of the modern digital era.

The second level is new precision manufacturing processes, which improve existing processes and allow for greater precision unachievable with other techniques or technology outside the past capabilities. The third level is the true synergy, which is taking advantages of new compositions together with new processes leading to materials and capabilities not possible before these technologies.

The fusion of advanced refractory materials with digitally enhanced precision manufacturing marks a significant leap forward in industrial capability. As we embrace automation, smart sensors, and AI, the materials and techniques used today are not only more efficient but also smarter and more sustainable. This convergence is essential to meet the demands of modern industry in sectors requiring extreme performance and flawless precision.

A significant contribution to the first level is thermal protection systems (TPS). These TPS are designed for hypersonic flight and have leading edges exposed to maximum temperatures exceeding 3000 °C. There is no currently existing material comparison with the TPS detailed in sections 1.2 and 4.2. These materials have a combination of composition, properties, and performance not found in existing products. There are similarities with existing materials composed of

C/C composites with a SiC coating, e.g. LRSI, but these composites are unreinforced. Compared to unreinforced, there is better oxidation resistance in nonoxidizing environments. There is also better erosion resistance because the materials are harder and have a rigid fiber reinforcement which minimizes crack propagation. The TPS detailed in section 4.2 also have much lighter weights. These TPS represent a significant leap forward in capabilities.

Advances in material and composition, process and technique is a significant contribution in the crucibles and molds area. The materials and composition included new types of c-pyro and silica carbonaceous investment casting (IC) magmas, CO and C-O systems for various temperatures and calcined, low cost, high purity, high refractoriness, and local raw materials. The processes and techniques involved are new ways of shaping, modus of furnace heating, retaining salt molds, and retractable holding furnaces. These materials, new designs, and combinations in below twenty percent requirements for expensive high purity bonding agents are either none or of little non-compliance with the noted standards and regulations on silica dust contamination, and significant environmental friendliness. All these advancements can be applied to molding metals of up to 2200 °C melting temperatures. Furthermore, the same bonding agents spread outside the OC IC HS despair on the future of the IC technology is easily deployable. So far the IC mechanically fragile nature poses a great hurdle, but the metamorphosed technology can perform IC with manufacturable molds, and the work itself explores possibilities for new mold projects.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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