

EMERGING TRENDS IN MECHANICAL ENGINEERING AND ADVANCED ENGINEERING APPLICATIONS

Editor:

Prof. Dr. Hasan KÖTEN



BİDGE Yayınları

**Emerging Trends in Mechanical Engineering and Advanced
Engineering Applications**

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PREFACE

Mechanical engineering, as one of the oldest and most comprehensive branches of engineering, continues to evolve in response to rapid technological innovation, digital transformation, and sustainability. The integration of smart manufacturing systems, advanced computational methods, artificial intelligence, and interdisciplinary engineering approaches has expanded the traditional boundaries of mechanical engineering, enabling the development of innovative solutions in design, analysis, manufacturing, and maintenance processes. Contemporary research in mechanical engineering is increasingly focused on advanced manufacturing technologies, energy systems, robotics and automation, mechatronics, computational engineering, artificial intelligence-based engineering applications, advanced materials, thermal sciences, fluid mechanics, machine design, and sustainable engineering practices. The emergence of Industry 4.0 and digital transformation has further strengthened collaboration between academia and industry, highlighting the importance of translating scientific research into practical engineering solutions and technological innovation. In this context, *Emerging Trends in Mechanical Engineering and Advanced Engineering Applications* has been prepared to bring together recent scientific research and technological developments in the field of mechanical engineering, providing a comprehensive reference for researchers, academics, graduate students, engineers, and industry professionals. The chapters included in this volume cover a wide range of topics,

including machine design, manufacturing technologies, computer-aided engineering, energy systems, thermodynamics, fluid mechanics, heat transfer, robotics, automation, mechatronic systems, artificial intelligence applications, advanced materials, and sustainable engineering solutions. Authored by experts in their respective fields, these contributions present the current state of knowledge while offering valuable perspectives that can inspire future academic research and industrial innovation. We believe that this book will contribute to the dissemination of scientific knowledge, strengthen interdisciplinary collaboration, and serve as a valuable resource for researchers and practitioners working in mechanical engineering and related disciplines. We sincerely thank all chapter authors for their valuable contributions, the reviewers for their constructive evaluations, and the editors and technical teams whose dedicated efforts made this publication possible. We also acknowledge the institutions and organizations that continue to support scientific research and technological advancement. It is our hope that this volume will serve not only as a current reference in mechanical engineering but also as a source of inspiration for young researchers, fostering innovative ideas, strengthening collaboration between academia and industry, and contributing to the development of sustainable, intelligent, and high-performance engineering systems for the future.

Prof. Dr. Hasan KÖTEN

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CHAPTER 1

BEYOND THE LIMITS OF TRADITIONAL METALLURGY: DESIGN PRINCIPLES, APPLICATIONS, AND FUTURE PERSPECTIVES OF HIGH-ENTROPY ALLOYS (HEAS)

HİLMİ TEKDIR¹

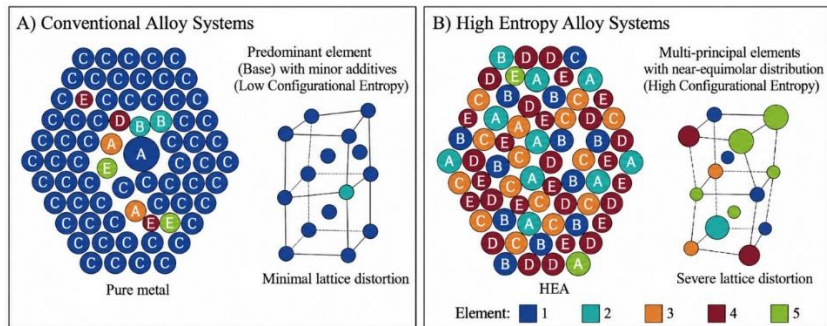
Introduction

Human history is closely tied to the materials we invent and use (H. Wang et al., 2024). For thousands of years, metallurgy was based on a fairly rigid rule: pick one primary metal and add small amounts of other elements to improve it. We add carbon to iron for strength or copper to aluminum for toughness, but the base metal always remains dominant (Krishna et al., 2024; D. Kumar, 2023). While effective, this single-based approach limits researchers to the very edges of alloy phase diagrams. The middle ground—where multiple elements mix in equal or near-equal amounts—was ignored for decades. Material scientists generally assumed that blending five or six elements in high concentrations would just produce brittle, unusable intermetallic phases (Zhao et al., 2025).

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Around 2004, that assumption changed. Two research groups, working independently under Jien-Wei Yeh and Brian Cantor, proposed blending multiple principal elements without a single dominant base (Jiao et al., 2024). They called these new systems High-Entropy Alloys (HEAs). Typically composed of five or more elements in near-equiatomic ratios, HEAs rely on a thermodynamic mechanism rather than strict chemical ordering. By pushing the configurational mixing entropy high enough, the total Gibbs free energy of the system drops. This thermodynamic shift prevents the expected brittle intermetallics from forming. Instead, the mixed elements settle into simple, stable solid solutions like face-centered cubic or body-centered cubic structures (Y. Sun & Dai, 2024; Y. F. Yang et al., 2025). A comprehensive visual comparison of these competing atomic architectures and their effect on crystal lattice regularity is provided in Fig. 1.

Fig. 1. Comparison of atomic configurations and lattice distortions in (A) conventional alloys and (B) high-entropy alloys (HEAs).



(D. Kumar, 2023)

What makes these alloys behave differently boils down to four core effects. First, the high entropy effect stabilizes the solid solution structure itself (S. Kumar, 2024). Second, atomic movement within this crowded, complex matrix is difficult, creating a sluggish diffusion effect that keeps the microstructure stable even at elevated

temperatures (Verma et al., 2024). Third, forcing atoms of completely different sizes to share a crystal lattice causes severe lattice distortion. This internal strain blocks dislocation movement, making the material surprisingly strong (H. Wang et al., 2024). Lastly, the so-called "cocktail effect" means the final alloy often performs much better than a basic mathematical average of its constituent parts, yielding unique and highly synergistic mechanical properties (Jiao et al., 2024).

This chapter provides a structured overview of high-entropy alloys, tracing how they are designed, built, and utilized. Following this introduction, we will examine modern manufacturing routes like additive manufacturing and arc melting. From there, the text covers the specific mechanical benefits of HEAs, focusing on their cryogenic performance and wear resistance. We then look at where these materials fit in industrial applications, from aerospace components to biomedical implants, before addressing the practical cost and production challenges that still limit their widespread use. The final section looks ahead to how artificial intelligence and sustainable design methodologies might solve these remaining issues.

Design Principles and Manufacturing Technologies

Predicting phase stability in traditional alloys is relatively straightforward since it largely relies on binary phase diagrams and the crystal structure of a single base metal. This simplicity vanishes when five or more elements are mixed in near-equimolar ratios (Ron et al., 2023; H. Wang et al., 2024). Researchers must navigate billions of possible combinations using specific empirical and thermodynamic parameters to successfully stabilize targeted single-phase solid solutions (Wu et al., 2026).

The Valence Electron Concentration (VEC) serves as a primary indicator for anticipating the crystal structure. Empirical

data demonstrates that an average VEC above 8.0 promotes Face-Centered Cubic (FCC) phases. Values below 6.84 stabilize Body-Centered Cubic (BCC) structures, while intermediate values typically result in mixed phase configurations (J. T. Ren et al., 2023). Atomic size mismatch and mixing enthalpy are equally critical for phase stability. The variation in atomic radii must remain below 6.6% to prevent severe lattice strain from triggering brittle intermetallics. The mixing enthalpy should also be neutral or slightly negative to avoid undesired phase separation (Ron et al., 2023). Modern metallurgical design heavily incorporates computational tools like CALPHAD, Density Functional Theory (DFT), and machine learning to rapidly screen these parameters. This shift allows for the reverse-design of complex alloys without relying on costly trial-and-error iterations (Jiao et al., 2024; L. Sun et al., 2024).

Vacuum Arc Melting (VAM) remains the most common method for the laboratory-scale synthesis of high-entropy alloys (Jiao et al., 2024). The constituent elements are melted in a water-cooled copper crucible under a vacuumed argon atmosphere to prevent oxidation. Blending refractory metals like tungsten with volatile elements such as aluminum creates severe homogeneity issues (S. Kumar, 2024). The resulting ingot is repeatedly flipped and re-melted to counter elemental segregation. The subsequent slow cooling process often leads to coarse dendritic structures where high-melting elements cluster in the dendritic cores. Extensive high-temperature homogenization followed by rapid quenching is therefore necessary to restore a uniform single-phase solid solution.

Researchers frequently utilize solid-state powder metallurgy to completely bypass the macro-segregation issues associated with melting (Krishna et al., 2024). Mechanical alloying subjects elemental powder mixtures to intense plastic deformation, fracturing, and cold welding inside high-energy ball mills. This mechanical forcing drives atomic diffusion even at room

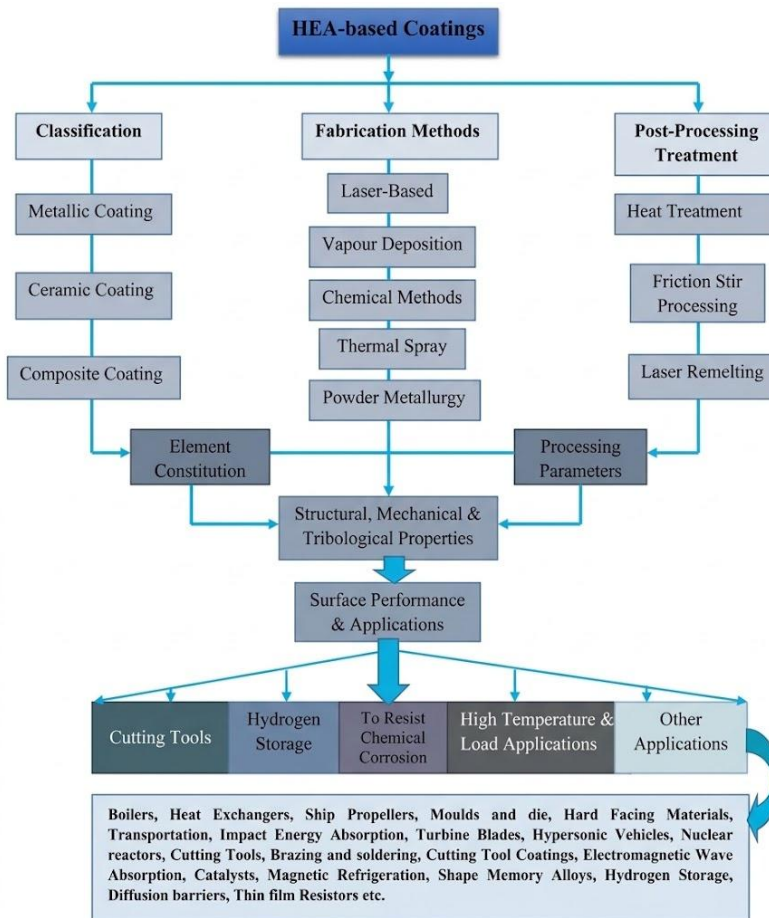
temperature, yielding nano-sized and chemically homogeneous solid solution powders (L. Yang et al., 2025). These powders are consolidated into bulk components using advanced techniques like Spark Plasma Sintering (SPS) or Hot Isostatic Pressing (HIP). SPS applies simultaneous axial pressure and high electrical current to achieve near-theoretical density in seconds without causing excessive grain growth. Introducing ceramic phases like titanium carbide during this stage creates HEA composites with exceptional industrial wear resistance (Wu et al., 2026).

Unlike the slow cooling of traditional casting processes, additive manufacturing (AM) provides ultra-fast cooling rates ranging from 10^3 to 10^6 K/s. This rapid solidification effectively suppresses elemental segregation and enables the direct fabrication of complex HEA components as fully saturated solid solutions (Ron et al., 2023). Powder Bed Fusion (PBF) systems, which include laser (LPBF) and electron beam (EBM) methods, selectively melt thin layers of powder. LPBF creates incredibly fine cellular structures that offer exceptional yield strength. EBM's high vacuum environment and highly heated build plate prevent thermal cracking in brittle refractory alloys (Bourell, 2016). Directed Energy Deposition (DED) feeds powder directly into a moving melt pool. Its greatest functional advantage is in-situ alloying. Engineers can print functionally graded HEA structures in a single continuous build by adjusting the feed rates from multiple powder hoppers on the fly (Blakey-Milner et al., 2021).

The high material cost of rare constituent elements restricts the mass production of large monolithic HEA components. A highly economical alternative involves applying a thin, high-performance HEA coating over conventional steel or aluminum substrates (S. Kumar, 2024). Fig. 2 provides a comprehensive summary of the classification, fabrication techniques, and post-processing

treatments of HEA-based coatings alongside their resulting structural properties and wide-ranging industrial applications.

Fig. 2. Summary of HEA-based coatings: coating materials, fabrication techniques, post-processing treatments, properties, and specific industrial applications.



(S. Kumar, 2024)

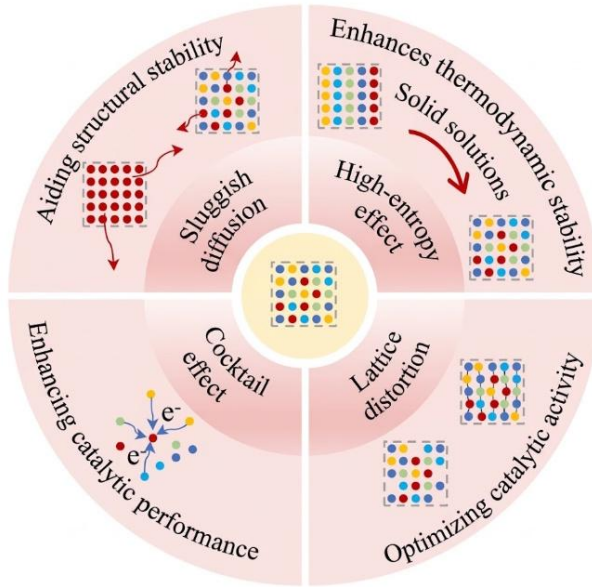
Vacuum techniques like magnetron sputtering use plasma bombardment to deposit super-hard, amorphous protective films. Laser cladding is generally preferred to build thicker and

metallurgically bonded protective layers for heavy industrial wear applications (Han et al., 2025). Recent breakthroughs also include highly transient methods like Carbothermal Shock (CTS). Researchers can successfully synthesize flawless single-phase HEA nanoparticles comprising up to eight traditionally immiscible elements by rapidly heating precursors to 2000 K and quenching them in mere milliseconds (L. Yang et al., 2025).

Exceptional Mechanical and Physical Advantages of HEAs

Strength and ductility typically function as mutually exclusive mechanical properties in conventional engineering metals. Increasing a material's yield or tensile strength generally compromises its capacity for plastic deformation, and vice versa (D. Kumar, 2023; Tang et al., 2023). High-entropy alloys stand out as a rare class of materials capable of overcoming this fundamental strength-ductility trade-off through their unique multi-principal element architecture and distinct microstructural hardening mechanisms. The four fundamental core effects governing these exceptional physical, mechanical, and thermodynamic properties are schematically summarized in Fig. 3. Forcing five or more principal elements with different atomic radii and bonding energies into the same lattice points generates severe localized lattice distortion (Zhao et al., 2025). These localized elastic strain fields create a massive Peierls-Nabarro barrier against dislocation movement, pushing solid solution hardening to maximum theoretical levels (S. Kumar, 2024). Body-Centered Cubic (BCC) HEAs and Refractory HEAs (RHEAs) leverage this severe lattice strain to achieve extraordinary yield strengths exceeding 1500–2000 MPa (D. Kumar, 2023; S. Kumar, 2024).

Fig. 3. Schematic overview of the four core effects of HEAs and their fundamental influence on thermodynamic, structural, and functional performance.



(L. Sun et al., 2024)

Furthermore, Face-Centered Cubic (FCC) HEAs, such as the Cantor alloy (FeCrMnNiCo), possess an exceptionally low Stacking Fault Energy (SFE). This low SFE triggers the formation of nano-scale deformation twins alongside conventional slip during plastic deformation (Twinning-Induced Plasticity - TWIP) (Tang et al., 2023). These twin boundaries act as dynamic barriers to dislocation motion, generating a dynamic Hall-Petch effect that continuously strain-hardens the material and imparts massive ductility. Metastable dual-phase HEAs can also exhibit a Transformation-Induced Plasticity (TRIP) effect, where the soft FCC phase transforms into a hard martensitic phase under stress, simultaneously increasing both yield strength and total elongation (S. Kumar, 2024). These synergistic TWIP and TRIP mechanisms allow HEAs to resist thermal softening and adiabatic shear banding even under high strain rate dynamic loading like ballistic impacts.

Material loss due to friction and wear causes severe economic damage in mechanical systems (B. Wang et al., 2026).

HEAs offer far superior tribological performance compared to traditional alloys due to their high hardness, excellent work-hardening capabilities, and chemical complexity. At room temperature, the sliding wear resistance of HEAs correlates strongly with their hardness and load-bearing capacity, conforming to Archard's law (D. Kumar, 2023). Incorporating hard B2/Laves phase precipitates or carbide reinforcements significantly reduces delamination wear caused by adhesion and abrasion. When subjected to high-temperature sliding contact ($>500\text{--}800^\circ\text{C}$), the friction and thermal energy trigger the formation of a dense protective oxide layer, known as a glaze layer. Complex oxide films containing elements like MoO_3 or V_2O_5 act as solid lubricants, drastically lowering the friction coefficient (COF) and protecting the substrate (D. Kumar, 2023). Researchers also engineer self-lubricating HEA composites by adding solid lubricants like Ag, BaF_2 , or graphene to the matrix, providing synergistic surface protection across extremely broad temperature ranges.

While conventional steels and BCC metals suffer from brittle fracture (Ductile-to-Brittle Transition - DBTT) as temperatures drop, single-phase FCC HEAs like CrCoNi exhibit extraordinary fracture toughness and increased ductility at cryogenic temperatures such as 77 K (liquid nitrogen) and 4.2 K (liquid helium) (Tang et al., 2023; Y. F. Yang et al., 2025). As the temperature decreases, nano-twinning becomes the dominant deformation mode, allowing the material to retain its fracture resistance and strain-hardening capacity in extreme cold. At the opposite thermal extreme, Refractory High-Entropy Alloys (RHEAs) composed of high-melting-point elements (W, Mo, Nb, Ta) exhibit higher yield strength and superior creep resistance than conventional nickel-based superalloys at temperatures exceeding 1200°C (S. Kumar, 2024; Wu et al., 2026). The sluggish diffusion core effect inherent to HEAs severely restricts atomic

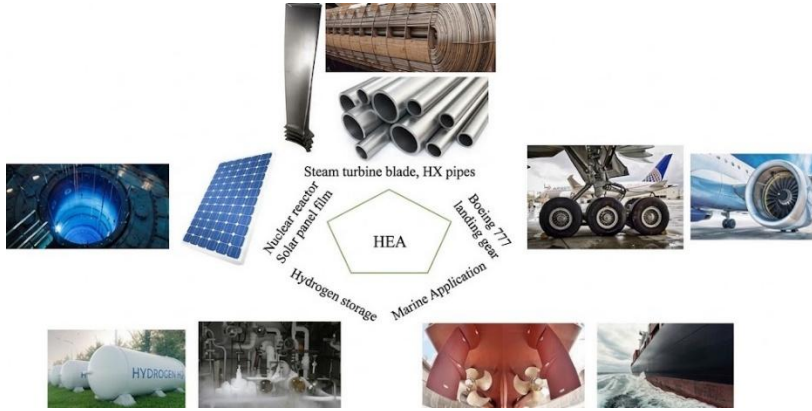
mobility at these high temperatures, delaying grain growth and maintaining long-term microstructural phase stability.

Corrosion resistance in traditional alloys is frequently compromised by elemental segregation and secondary phase precipitation at the grain boundaries. HEAs overcome this vulnerability through their multi-element solid solution structures and chemical disorder, which promote the rapid nucleation of highly homogeneous, continuous, and firmly anchored passive oxide films (Krishna et al., 2024). Elements like Cr, Ni, Mo, and Ti act as strong passivation formers, creating a robust barrier against aggressive corrosive media. Electrochemical polarization tests conducted in harsh environments, such as 3.5 wt% NaCl solutions or highly acidic media, reveal that HEAs possess a higher corrosion potential, higher pitting initiation potential, and a lower corrosion current density compared to 304 and 316L stainless steels (S. Kumar, 2024; Y. F. Yang et al., 2025). Furthermore, amorphous HEA films produced via magnetron sputtering eliminate grain boundaries and crystal defects entirely, offering exceptional pitting corrosion resistance and unparalleled passivation stability.

Industrial and Technological Application Areas

The unique core effects possessed by high-entropy alloys (HEAs) and materials (HEMs) have enabled the integration of multifunctional superior properties into a single structure, such as exceptional mechanical strength, thermal stability, high wear resistance, corrosion resistance, and radiation tolerance (D. Kumar, 2023; H. Wang et al., 2024). These advanced properties have made HEAs a critical alternative in harsh service conditions where traditional metals and nickel-based superalloys have reached their performance limits (Krishna et al., 2024; J. Ren et al., 2025). Fig. 4 illustrates the diverse industrial and technological application areas of these advanced alloys.

Fig. 4. Different applications of high entropy alloys.



(Krishna et al., 2024)

In the aviation, aerospace, and defense industries, there is a need for materials exhibiting high-temperature resistance, low density, high creep resistance, long fatigue life, and thermal shock stability (J. Ren et al., 2025; Y. F. Yang et al., 2025). The fundamental way to increase the efficiency of aero-engines and gas turbines is to increase the turbine inlet temperature. However, the widely used nickel-based superalloys today (Inconel 718, Haynes 230, etc.) have reached their operating limits, which correspond to approximately 80% of their melting temperatures (S. Kumar, 2024). Refractory High Entropy Alloys (RHEAs)—especially WNbMoTa , WNbMoTaV , $\text{AlMo}_{0.5}\text{NbTa}_{0.5}\text{TiZr}$, and HfNbTaZr systems—stand out as next-generation candidate materials for jet engine turbine blades, rocket nozzles, and thermal protection systems of hypersonic vehicles by maintaining their high yield strengths and phase stabilities even at extreme temperatures above 1200°C (J. Ren et al., 2025). Furthermore, the development of Lightweight RHEAs provides a major advantage in reducing the total weight and fuel consumption of aircraft components by offering high specific strength (Y. F. Yang et al., 2025). In the defense industry, the high adiabatic shear band resistance and fracture toughness of HEAs are

utilized in the design of armor materials resistant to high-speed particle impacts and ballistic shocks. Alloys that do not lose ductility at high dynamic deformation rates and resist shear localization provide high impact energy absorption capacity in military armor plates and penetration protection systems (Liu et al., 2024; Tang et al., 2023).

In nuclear energy, fourth-generation reactors and fusion reactor designs require materials to operate safely for long periods under extreme neutron/ion radiation, high-temperature corrosion, and thermal stresses. When traditional austenitic stainless steels (e.g., 316H) are exposed to intense radiation in the nuclear reactor core, they undergo macroscopic void swelling, embrittlement, and radiation-induced hardening as a result of the accumulation of point defects (Cui & Zhang, 2023; H. Wang et al., 2024). In HEAs, on the other hand, severe lattice distortion and high chemical complexity rapidly dissipate the cascade energy in cascade collisions by altering the migration energies of point defects and shortening the electron mean free path. This situation promotes the defect recombination of the formed voids and interstitial atoms (M. Wang et al., 2023). Ion irradiation tests performed on Tungsten-based RHEAs, FeCoNiCrMn, and Ti-Zr based systems have revealed that these alloys exhibit at least an order of magnitude less void swelling compared to traditional steels and demonstrate extraordinary stability against radiation hardening (H. Wang et al., 2024). In order to maintain corrosion resistance under nuclear reactor accident conditions, HEA multilayer protective films such as AlCrMoNbZr/(AlCrMoNbZr)N are coated on the surface of zirconium alloy fuel rods using magnetron sputtering or arc coating methods. In addition, HEAs with a BCC crystal structure and a high proportion of Laves phase provide wide hydrogen reaction areas and are used as high-capacity and reversible hydrogen storage materials

in renewable energy storage systems (Krishna et al., 2024; J. Ren et al., 2025).

In machining processes, cutting tools are exposed to extreme friction, high temperatures, and abrasion at high cutting speeds (Li et al., 2022). In the Tungsten Carbide - Cobalt (WC-Co) systems widely used in classic hard metal cutting tools, Cobalt (Co) is a binder phase desired to be substituted due to strategic raw material costs, toxicity, and its softening tendency at high temperatures (S. Kumar, 2024). The integration of HEAs into the cermet matrix as a binder phase (HEA binder) or their application as a coating on hard cutting tool surfaces is a critical innovation in the manufacturing industry (Ron et al., 2023). Nitride and carbide-based HEA coatings composed of high melting point elements exhibit high-temperature hardness ($>20\text{-}40\text{ GPa}$), high thermal stability, and a low friction coefficient, significantly extending tool life in high-speed dry machining operations (Tang et al., 2023). FeCoCrNiB_x or FeCoNiTiAl_x coatings applied by laser cladding to provide resistance against thermal shocks and abrasion in injection molds, hot forging dies, and casting equipment increase wear resistance by preventing thermal cracking on mold surfaces (D. Kumar, 2023).

The traditional Ti-6Al-4V alloy used in orthopedic, dental, and cardiovascular implants has a high elastic modulus ($\sim 110\text{ GPa}$) compared to bone tissue, which can lead to a "stress shielding" effect and bone resorption (Emanuelli et al., 2025; R. Wang et al., 2022). Moreover, the release of Al and V ions in its structure into the body over time poses cytotoxicity and neurological risks (J. Ren et al., 2025). To overcome these limitations in the biomedical field, High Entropy Alloys (BioHEAs) such as Ti-Zr-Nb-Ta-Mo, Ti-Zr-Hf-Nb-Ta, and Ti-Zr-Ta-Hf-Nb-Sn, which contain no toxic elements and are fully biocompatible, have been developed (J. Ren et al., 2025). These biological HEAs, synthesized by Selective Laser Melting (SLM) or casting methods, maintain a high yield strength of over 1000 MPa

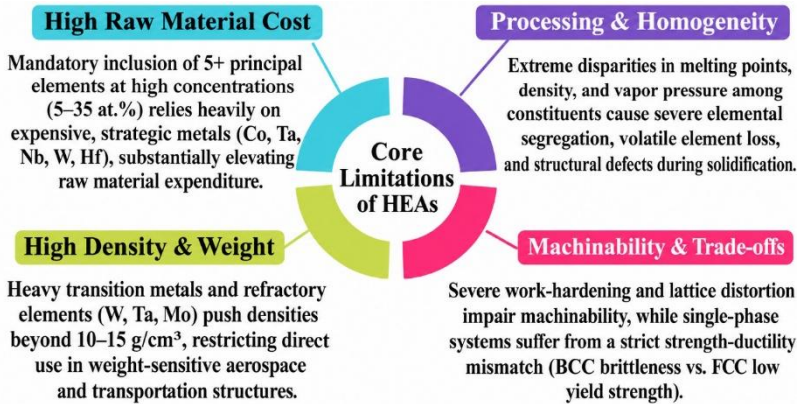
while lowering their elastic modulus down to 69 GPa, providing a perfect match with the elastic modulus of human bone (10-30 GPa). Thanks to the spontaneously passivating continuous oxide films formed on their surfaces in body fluid simulations, BioHEAs reduce the corrosion rate to levels of 10^{-4} mm/year, extending the life of the implant in the human body (L. Sun et al., 2024). Finally, $\text{Al}_{0.1}\text{CoCrFeNi}$ or $(\text{MoTa})_x\text{NbTiZr}$ systems, which offer high fatigue life and ductility in peripheral and coronary cardiovascular stent applications, prevent blood clotting and tissue inflammation, and are considered as next-generation intravascular stent materials (Han et al., 2025; J. Ren et al., 2025).

Current Limitations and Disadvantages

Despite their exceptional mechanical, thermal, and chemical attributes, high-entropy alloys (HEAs) face several critical bottlenecks and disadvantages when transitioning from laboratory-scale research to industrial and commercial mass production (D. Kumar, 2023; Y. F. Yang et al., 2025). Primary among these hurdles are the exorbitant costs associated with raw materials and synthesis processes. The classic definition of HEAs mandates combining at least five principal elements in equimolar or near-equimolar concentrations (5–35 at.%), which requires significant quantities of strategic and expensive metals such as cobalt (Co), titanium (Ti), ruthenium (Ru), niobium (Nb), tantalum (Ta), hafnium (Hf), and tungsten (W) (Krishna et al., 2024). Whereas conventional alloy systems utilize a single inexpensive base metal (such as Fe or Al) enriched with minor additions, the inclusion of costly elements as primary constituent matrix components in HEAs substantially inflates unit raw material expenditure, establishing a major commercial barrier for large-scale engineering applications. Consequently, recent research efforts have increasingly focused on designing low-cost HEA systems that substitute costly elements with economically viable alternatives like Fe, Al, Mn, and Cr (D. Kumar,

2023). A schematic summary of these major technological and economic bottlenecks is illustrated in Fig. 5.

Fig. 5. Schematic overview of the core technological, economic, and processing limitations of HEAs.



(Prepared by the author)

Beyond economic constraints, the chemical and physical complexity of multi-element systems introduces severe compositional homogeneity issues during manufacturing (Liu et al., 2024; Ron et al., 2023). Extreme disparities in melting temperatures, vapor pressures, and densities among constituents—such as volatile, low-boiling Al or Mn coexisting with refractory W, Mo, Nb, or Ta—frequently result in unmelted elemental inclusions, evaporative element loss, and pronounced macro- and micro-segregation during melting and casting. These processing anomalies degrade ingot quality by introducing porosity, microcracking, and structural defects, thereby complicating the reliable production of defect-free bulk HEA ingots and hindering industrial scalability.

Another physical drawback of HEAs pertains to high density and component weight. Refractory High-Entropy Alloys (RHEAs) developed for extreme high-temperature and nuclear environments often incorporate high proportions of heavy transition metals (W, Ta,

Mo, Nb), pushing bulk densities beyond 10–15 g/cm³ (S. Kumar, 2024; M. Wang et al., 2023). Such high mass density restricts their direct deployment as monolithic structural components in aerospace, automotive, and lightweight structural engineering where specific strength (strength-to-weight ratio) is paramount, necessitating targeted efforts toward lightweight RHEA design.

From a mechanical performance and manufacturability standpoint, achieving an optimal balance between strength and ductility remains problematic across many HEA compositions. Single-phase Body-Centered Cubic (BCC) HEAs exhibit extraordinary yield strength and hardness but suffer from severe room-temperature brittleness and premature failure, whereas single-phase Face-Centered Cubic (FCC) HEAs offer high ductility at the expense of low yield strength (Y. F. Yang et al., 2025). Additionally, severe lattice distortion and pronounced work-hardening rates accelerate tool wear and require excessive cutting forces during machining operations (cutting, drilling, milling) and thermo-mechanical processing (rolling, forging), severely impairing industrial machinability (Krishna et al., 2024). Addressing these interconnected cost, homogeneity, weight, and processing challenges remains crucial for advancing HEAs from academic exploration to widespread commercial deployment (S. Kumar, 2024).

Future Trends and Outlook

By dismantling the classical single-base paradigm, high-entropy alloys (HEAs) and the broader family of high-entropy materials (HEMs) have opened an almost boundless design landscape comprising billions of potential compositional states (Schweidler et al., 2024). Navigating this multi-element parameter space through conventional trial-and-error experimentation is practically impossible (J. Ren et al., 2025). To overcome this

bottleneck, inverse design frameworks that integrate machine learning (ML), artificial intelligence (AI), Density Functional Theory (DFT), and CALPHAD calculations have moved to the center of materials discovery (L. Sun et al., 2024). These data-driven models look beyond traditional empirical parameters like atomic size mismatch or valence electron concentration. By employing holistic descriptors such as Entropy-Forming Ability (EFA) and configurational ordering metrics, algorithms can accurately forecast the formation of stable single-phase solid solutions and high-performance eutectic microstructures. Coupling high-throughput computational screening with automated synthesis pipelines drastically accelerates discovery, condensing timeline horizons from years down to days (Schweidler et al., 2024; Y. Sun & Dai, 2024).

The role of AI extends far beyond composition prediction. Autonomous self-driving laboratories are beginning to optimize processing parameters and microstructural evolution in real time (Ron et al., 2023). When paired with advanced additive manufacturing techniques like Laser Metal Deposition (LMD), machine learning models capture the rapid solidification kinetics and transient phase transformations occurring during fabrication, preventing defect formation (S. Kumar, 2024). Continuous feedback loops between experimental characterization and predictive algorithms enable multi-dimensional property mapping—from pinpointing catalytic active sites to predicting high-temperature creep and cryogenic toughness. Consequently, the field is shifting away from empirical trial-and-error toward application-driven, tailor-made smart material architectures (L. Sun et al., 2024).

Sustainability and circular economy principles will dictate the commercial viability of future HEA developments. Early HEA formulations relied heavily on scarce, expensive, and toxic strategic elements like cobalt, tantalum, ruthenium, and hafnium, creating economic and environmental hurdles (Y. F. Yang et al., 2025).

Modern research is pivoting toward "green HEAs" that substitute these critical raw materials with Earth-abundant, non-toxic alternatives such as iron, aluminum, manganese, chromium, and titanium (Y. F. Yang et al., 2025). Additionally, the tight atomic bonding inherent to single-phase HEAs presents unique recycling challenges at end-of-life, requiring energy-intensive chemical separation. Future engineering efforts must prioritize scrap-tolerant alloy designs and low-carbon synthesis routes that directly utilize recycled metal feedstocks without sacrificing structural integrity (D. Kumar, 2023).

Reflecting on the progress made over the past two decades since the high-entropy concept was first introduced, the field has undeniably evolved from a theoretical curiosity into a comprehensive material platform spanning metals, ceramics, functional coatings, and nanoparticles. The core phenomena driving these materials—high entropy, sluggish diffusion, severe lattice distortion, and cocktail interactions—have repeatedly demonstrated their capacity to shatter the limits of conventional metallurgy across the aerospace, nuclear, tooling, and biomedical sectors. Although practical challenges related to cost, processing homogeneity, weight, and machinability still pose hurdles for mass production, the synergistic integration of additive manufacturing, powder metallurgy, and AI-driven inverse design offers a clear roadmap to resolving these barriers. Ultimately, driven by the dual imperatives of digitalization and environmental stewardship, high-entropy materials are uniquely positioned to cement their legacy as one of the most transformative and defining engineering breakthroughs of the twenty-first century.

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CHAPTER 3 ADVANCED CERAMIC MATRIX COMPOSITES AND INCONEL SUPERALLOYS IN AEROSPACE ENGINEERING: RECENT DEVELOPMENTS

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Abstract

Advanced ceramic matrix composites and Inconel superalloys are two types of materials that are used for making parts in aerospace applications where the parts must handle extreme heat, high pressure, and harsh chemical environments. This chapter takes a detailed look at important changes from 2010 up to 2026, showing how the way materials are created, and their structure relate to how they wear away, how they are kept safe, and where they are applied. For CMCs, it explains how the fibers link with the matrix, how the material becomes dense, how it is covered to keep it safe from heat and chemicals, and how cracking, oxidation, and mechanical stress affect each other. The chapter examines how aerospace applications use parts that don't move inside engines, parts that spin in engines, components used in rockets, and materials that guard against very high temperatures. It also clearly separates what is found in labs, what is tested on real parts, and what is really used in the field. New techniques such as modeling based on material structure, X-ray imaging, sound-based testing, and using machine learning to analyze material properties are checked to see how reliable and trustworthy they are for use. To move forward, it's important to make sure materials can be made in a consistent way, that coatings stick properly to them, that materials can hold up when exposed to heat, pressure, and chemicals together, and that their surfaces can be easily examined. Choosing the right material is a key decision, as it affects how heat is managed, the environment it will be in, how it's made, and how it will be maintained. Future progress will depend on converting better materials into parts that are made the same way each time, stay strong for a long time, and are affordable to use in aerospace.

Keywords: Ceramic matrix composites; SiC/SiC; Inconel superalloys; aerospace engineering; additive manufacturing; environmental barrier coatings; high-temperature durability; fatigue; nondestructive evaluation; component qualification.

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1. Introduction

Aerospace propulsion systems rely on materials that can withstand high heat and tough environmental conditions while handling mechanical stress. To make the engine work better, the materials used need to stay strong and effective even when things get really hot. At the same time, these materials have to be light, last a long time, easy to make, and dependable. These requirements are linked: a material that can withstand high temperatures may not work well for a part if it doesn't resist damage, handle different environments, or maintain good quality when made consistently. This is especially important in propulsion systems because picking the correct material influences both the maximum heat the system can handle and the way the supporting structures are built. CMCs combine ceramic bases, strong fibers, and special layers between them to help protect against damage when temperatures are very high. Superalloys get their strength and ability to resist wear from their special chemical composition and carefully controlled internal structure. A proper comparison between these materials should look at more than just their strength or the highest temperature they can handle. How well a part works depends on how the material handles ongoing stress, repeated temperature changes, any flaws, the surface condition, and being in certain environments. For example, research on Inconel 718 made through additive manufacturing has examined how heat treatment and design issues influence fatigue performance. Studies on coated SiC-based systems have found that the characteristics of the base material can affect how oxidation occurs within the coating. These results show that considering the material, how it's made, the protective layers, and the conditions it's used in all together is a useful way to think about parts [4, 5]. The interest in using ceramic matrix composites (CMCs) in aerospace applications stems from the ability to combine the heat-resistant properties of ceramics with a structure that inhibits the uncontrolled spread of cracks. This is very important for creating strong CMC parts because how damage forms inside can be just as important as how much weight the material can support [3]. A major advancement in this field came from Bale et al., who used synchrotron X-ray microtomography to observe how damage changed when materials were under stress at very high temperatures, up to 1750°C. Their work provided three-dimensional images of internal cracks under extreme conditions, creating a new experimental method to study damage and enhance failure models. The temperature they measured isn't the same as the real temperature that an aerospace part can safely work with [3]. Protecting the material from the environment is also an important part of creating CMCs. Research from the early part of this time already considered this by focusing on how to design coatings. This early research shows that making ceramic composites always required considering both the material's strength and its ability to handle environmental conditions [6]. New studies explain that you can't properly evaluate a protective coating by itself without taking into account the material it's used on. Ardrey et al [5] looked at environmental barrier coatings on various SiC materials and checked how these coatings performed when the materials were exposed to oxidation, comparing them to coated CMC samples. The coated CMCs grew an oxide layer more quickly compared to the pure SiC samples used in the study. This finding shows that using simple, single-material test samples may not accurately show how coatings behave on real composite materials [5]. These studies indicate that progress in CMC technology is influenced by how internal damage develops and how the coating and base material react chemically. So, this chapter examines reinforcement design, the process of making the material, how the layers work together, and ways to guard against environmental factors, all as important parts of designing the material. CMCs and Inconel superalloys, although they differ in how they strengthen and experience damage, need to be evaluated using a common assessment framework. For CMCs, the key factors that influence their performance include the

structure of the reinforcing material, the state of the matrix, the layers between different phases, any internal flaws, and the protective layers applied on their surface. In the case of Inconel made through additive manufacturing, important features include the microstructure formed during solidification, the types and amounts of defects present, the heat treatment applied, and the condition of the surface. Research from both fields indicates that how well these materials work depends a lot on the features that are created or changed during their making process [3–5,7,8]. The way we look at this is done step by step: first we look at how it's processed, then its tiny structure, then how it gets damaged, and finally how well it performs. The processing of a material affects its initial condition. Damage happens when these microstructural features interact with their surrounding environment. In the end, how well the component works is because of all the damage it builds up over time as it's being used. A quick test done at high heat doesn't tell you the same thing as checking how long the material can last over time. Testing a coating on just one piece of material doesn't mean the same results will work for a composite material that has added reinforcing parts. This chapter examines the developments and improvements that happened between the year 2010 and September 2026, with a particular emphasis on ceramic matrix composites (CMCs) used in the aerospace sector and certain types of Inconel superalloys. It looks at the better quality of the materials used, the new ways of making the products, how the materials inside structure are managed, the use of special layers to protect them, how well they work under physical stress, and their strength against tough weather and environments. Researchers look at the results of different studies by considering the exact situations and environments where the experiments took place. These results back up a way of thinking that considers the material used, how it's made, the protective coatings, and the conditions it's used in all together [4, 5]. The interest in using ceramic matrix composites (CMCs) in aerospace stems from the ability to combine the heat-resistant properties of ceramics with a structure that inhibits the uncontrollable spread of cracks. In materials that have long fibers, the way the fibers and the surrounding material work together is very important for how damage starts when the material is being stretched or pushed. Instead of seeing the material as one solid ceramic, you need to understand how cracks begin and affect each other in a complicated structure.

2. Material Architectures and Microstructural Foundations

The way ceramic matrix composites and Inconel superalloys perform is affected by structural features that exist at different levels of scale. In ceramic matrix composites, these structures include individual fibers, the layers that form between the fibers and the surrounding matrix material, the matrix itself, any pores present, and how the fiber bundles are organized. For Inconel alloys, the structure is made up of a solid-solution matrix, the small particles that help make the material stronger, the boundaries between grains, areas where certain elements are concentrated, and any imperfections that might form during the manufacturing process. Understanding these structural elements is really important because they explain why materials that have similar chemical makeup can behave differently in terms of their mechanical properties once they are made and subjected to high temperatures.

2.1. Classification of Aerospace Ceramic Matrix Composites

A continuous-fiber ceramic matrix composite, or CMC, is a type of material that combines a ceramic base with fibers woven throughout it. These fibers are carefully positioned to help carry the weight and control how any cracks might spread through the material. When it comes to naming these composites, there's a standard format that usually starts with the kind of fiber used,

followed by the type of ceramic that makes up the main body of the material. For instance, "SiC/SiC" means both the fibers and the matrix are made from silicon carbide. In contrast, "C/SiC" refers to a composite where the fibers are made of carbon, but the matrix is still silicon carbide. Although these names offer a quick overview of the main parts, they don't fully capture all the details about the material. To really understand and properly describe a CMC, you need to consider more than just the basic components. Factors like the strength and consistency of the fibers, the chemical makeup of the layer between the fibers and the matrix (known as the interphase), how the fibers are arranged, how the matrix is made, and the amount of air pockets or voids that might be left after the manufacturing process are all important. In the aerospace industry, there are three main kinds of CMCs that are often used: SiC/SiC, C/SiC, and oxide/oxide composites. What makes each of these materials unique isn't just about their chemical composition, but also how their internal structures work together to manage stress, handle damage, and withstand the tough conditions found in aerospace applications.

2.1.1. Silicon carbide fiber-reinforced silicon carbide composites

SiC/SiC composites are made by using silicon carbide (SiC) fibers as the strengthening component and a SiC-based material as the matrix that holds these fibers together. This matrix helps in distributing the forces acting on the composite, and it also defines the overall shape of the final part. Typically, there is a special layer, known as an interphase, that is carefully designed between the fibers and the matrix. This interphase is very important because it controls how cracks in the matrix behave. If a crack forms in the matrix, the interphase can guide it in a different direction, preventing it from spreading through the fibers. This redirection helps maintain the fibers' ability to perform their function even when the matrix has cracked. Research on interphases that include boron nitride has shown that changing the thickness and structure of these layers can significantly affect the overall behavior of the composite [9, 10]. Additionally, the matrix itself can vary depending on the method used to create the composite. For example, some techniques like melt-infiltration might leave behind some silicon along with SiC, while other methods can lead to different patterns of pores and matrix composition. A detailed examination of a three-dimensional woven SiC/SiC composite revealed that the matrix can consist of multiple types of phases, such as both SiC and silicon [11]. Because of this, the term "SiC/SiC" should not be interpreted to mean that the matrix is entirely uniform and solid throughout [11].

2.1.2. Carbon fiber-reinforced silicon carbide composites

C/SiC composites are created by mixing carbon fibers as the reinforcing material with a matrix made of silicon carbide (SiC). Developing these composites requires thoughtful planning of the structure of the reinforcement and taking steps to protect the material from environmental damage. For example, a study discussed in the Introduction section explored ways to shield C/SiC composites from harmful exposure to dry air and moisture [6]. The mechanical performance of these composites is also affected by how the fibers interact with the matrix. Research on chemically vapor-infiltrated C/SiC composites with multiple layers between the fibers and the matrix revealed that the way pores form between groups of fibers and individual fibers depends on the structure of the reinforcement. This relationship is crucial because the structure affects both how well the material can handle mechanical stress and the way the matrix flows into the spaces between the fibers. Therefore, modifying the design of the textile structure impacts more than just the direction in which the fibers are arranged [12].

2.1.3. Oxide fiber-reinforced oxide composites

Oxide or oxide composite materials usually consist of alumina-based fibers combined with an oxide matrix. A crucial approach in developing these composites is the deliberate creation of a porous matrix. This porosity plays an important role in managing how cracks form and spread, which is different from non-oxide composites that depend on a weaker coating on the fibers to reach similar outcomes. In this case, the porosity in the matrix is a purposeful feature of the material's design, intended to increase its resilience when it experiences damage, rather than being an unwanted byproduct of the manufacturing process. Farhandi and their research group explored this method by using Nextel 610 fibers paired with a porous alumina matrix. Their study showed that fine-tuning the sintering process, which refers to how the material is heated and shaped, can actually boost the tensile strength of the composite. Moreover, this adjustment helps keep porosity at a higher level while also decreasing the chance of cracks appearing during the sintering stage. This shows that reaching maximum density is not always the best strategy for oxide ceramic matrix composites. Instead, the best design requires a careful balance between the strength of the matrix, the protection provided to the fibers, and the material's capacity to deal with and recover from damage [13].

2.2. Fibers, Matrices, Interphases, and Reinforcement Architectures

2.2.1. Interphase-controlled load transfer and damage accommodation

The interphase is a particular, limited region of material that exists between a fiber and the matrix around it. On the other hand, the interface is the actual line or surface where two different materials or components meet. It is very important to understand the difference between these two terms because an engineered interphase can contain several layers, which in turn create multiple interfaces. In the case of reinforced ceramics, designing the interphase requires a delicate balance between how well the load is transferred from the matrix to the fiber and how effectively the interphase can reduce stress in the local area through processes like debonding and sliding. Qiu and their team, as mentioned in reference [10], demonstrated this balance in SiC/SiC composites that featured PyC/BN interphases. Their research found that increasing the thickness of the pyrolytic carbon layer from 0.10 to 0.30 micrometers initially improved the material's performance, but after a certain point, the bending strength and fracture toughness started to drop. The researchers explained this unexpected behavior as a result of a conflict between the stress relief the interphase offers and the efficiency of load transfer. This discovery shows an important point: just increasing the thickness of the interphase doesn't always lead to better overall performance for the composite material [10]. Moreover, when improving the interphase, it is important to take into account the conditions the material will face in its actual use. A study from 2026 examined BN/SiC dual-layer interphases and looked at how changes in the thickness of the SiC layer affected tensile properties under high-temperature and oxidative environments [14]. By evaluating the design of the interphase during exposure to these conditions, this method connects the mechanical performance of the composite to the specific conditions the interphase must withstand, making sure it functions properly [14].

2.2.2. Matrix porosity and processing-induced heterogeneity

Porosity affects how composites behave because of where it is located, its shape, and how the parts are connected. A single number for porosity can't tell the difference between small pores inside the fiber groups and bigger gaps between the groups or cracks that happen during the making process. These features may work in different ways when it comes to local loading and how the matrix is formed. That's why it's important to do microstructural analysis along with density testing. The study on C/SiC mentioned earlier used X-ray computed microtomography to identify how pores were arranged in different structures [12]. These measurements give information that you can't get just by looking at the bulk density alone [12]. The understanding of porosity should still be tied to the specific material system. In porous-matrix oxide composites, some porosity is purposely included. In the study by Farhandi et al [13], using a two-step sintering process, they made mini-composites that had a tensile strength of 230 ± 27 MPa. This is higher than the 133 ± 8 MPa achieved with the traditional sintering method. These values are for the specific mini-composites that were tested, not for general design limits, but they show that better performance can come from managing shrinkage damage and how the matrix develops, rather than just focusing on making the material as dense as possible [13].

2.2.3. Reinforcement architecture and directional response

Fiber architecture determines how the main parts that carry the load are arranged in space. Describing a composite as being two-dimensional or three-dimensional is just the start of understanding its structure. When looking at the material, you also need to take into account how the fibers are arranged, how they cross each other, the curve in different areas, and where the parts with more matrix are located. Studies on three-dimensional woven SiC/SiC using images have connected the real mesostructure to the thermomechanical behavior that was measured in experiments [11]. This method allows for using models that are specific to each type of architectural structure instead of considering all woven composites as the same kind of material. It also helps link local structural features to the effective response observed at the specimen level [11].

2.3. Aerospace-Relevant Inconel Grades

The Inconel alloys discussed in this chapter don't all work in the same way to become stronger. Their actions are based on their makeup and the structure that forms during freezing, shaping, and heating processes. Inconel 718 and 625 are especially useful for comparison, while Inconel 939 shows the processing needs of a grade that is strongly strengthened by γ' phases.

2.3.1. Inconel 718

Inconel 718 has a main structure made of nickel-rich gamma matrix and other secondary phases, and the amount of these secondary phases depends on how the material was processed. The main hardening particles are gamma double prime and gamma prime, and the delta phase along with carbides may also be found. Therefore, understanding the alloy involves more than just knowing its stated chemical makeup. Ferreri et al [15] created a method using neutron diffraction to measure the amounts of γ , γ' , γ'' , δ , and MC carbides in Inconel 718 that had been processed in different ways. Their work shows how important it is to measure phase populations directly when looking at different manufacturing methods. Just having a heat treatment label doesn't mean two samples have the same amount or spread of strengthening materials [15]. In additively manufactured materials, solidification-induced segregation introduces another layer of complexity. Studies on how Inconel 718 is treated with solution treatment followed by aging found areas rich in niobium

that are not reactive, and looked at how the conditions during solution treatment influenced the formation of γ'' and γ' phases. So, having niobium available and being able to move it around is very important for understanding how the structure of the material forms during manufacturing and how it changes after it's been aged.

2.3.2. Inconel 625

Inconel 625 is usually seen as a solid-solution-strengthened alloy, but this doesn't mean its structure doesn't have precipitates during making or when it's being used. Additive manufacturing can cause local areas of higher solute concentration, which affects how the material reacts to later heat treatment. Lass et al [17] studied laser-welded Inconel 625 metal after heating it to 870 degrees Celsius for an hour to reduce stress. They saw a lot of the orthorhombic Ni_3Nb δ phase forming as rain during the solidification, especially in the areas between the dendrites that had more niobium and molybdenum. Their research shows that a thermal treatment used to reduce stress can also cause a major change in the material's structure [17]. Zhang et al [18] later linked the faster growth of the δ phase in Inconel 625 made through additive manufacturing to the uneven distribution of elements in certain areas. When they combined their microscopy, synchrotron measurements, and thermodynamic analysis, they found that precipitation happened much faster than it does in wrought material. This means that local chemistry plays a key role in designing heat treatment processes: the overall composition might meet the alloy's standards, but different areas of the microstructure can react in various ways during annealing [18].

2.3.3. Inconel 939

Inconel 939 is an alloy that is strengthened by the γ' phase, and it's important to clearly tell the difference between its original state after printing and its condition after being heat treated. Shaikh et al [19] studied Inconel 939 made using laser powder-bed fusion and found that the structure formed without any heat treatment had columnar grains and small dendritic structures, but they didn't see any γ' particles forming under the conditions they tested. This observation is important because the ability of an alloy to become stronger often doesn't happen right away after it is made. The heat treatment needed to create the right kind of precipitate is part of the process used to make the material. So, a part might have the right chemical makeup, but it still needs a lot of work on its internal structure before we can check if it's strong enough to be used in real applications.

2.4. Strengthening Mechanisms and Phase Stability

2.4.1. Strengthening precipitates and competing phases

The γ' and γ'' phases need to be told apart based on their crystal structure and what they do. In usual explanations, γ' is a type of ordered phase made up of $\text{Ni}_3(\text{Al}, \text{Ti})$, while γ'' is a different kind of phase based on Ni_3Nb with a unique crystal structure. The size, how they are spread out, and how much of the material they take up all effect how these alloys respond mechanically when they are strengthened by precipitation. In Inconel 718, γ'' , γ' , and δ cannot be considered as the same thing or used interchangeably to refer to the same strengthening particles. Even though γ'' and δ both have the same chemical makeup as Ni_3Nb , their shapes and how they interact with the surrounding material are different. The phase-resolved measurements by Ferreri et al [15] help in understanding their specific contributions and show how different processing steps affect the overall phase balance [15]. Niobium plays a key role because it can spread out in both the main structure and different secondary parts of the material. Research on Inconel 718 made using

additive manufacturing has looked at solution treatment and aging as steps that happen together. These steps change how elements are separated and later form precipitates [16]. To get the best results from aging the microstructure, you need to pay attention to the condition of the material you start with, instead of just applying an aging treatment without considering how the material solidified before [16].

2.4.2. Segregation and the evolution of local phase stability

Rapid solidification does not eliminate chemical heterogeneity. In the Inconel 625 studies mentioned earlier, areas rich in niobium and molybdenum created good spots for the δ phase to form [17,18]. The way things turned out shows that checking phase stability both in small parts and in the whole alloy is important. Homogenization can help reduce segregation, but it's important to check if it works well under the specific manufacturing conditions. Zhang et al showed that after doing a homogenization treatment, the δ phase was removed and the chemical makeup became more uniform. This evidence shows that thermal processing can be used to change the material's structure, not just to reduce leftover stress [17, 18].

2.5. Processing–Microstructure–Property Relationships

The evidence so far shows that both CMCs and Inconel alloys follow a common idea: the way they are processed creates certain structures that can help with one part of their performance but may harm another. In CMCs, changing the thickness of the interphase affects how the material handles stress and deals with damage. In oxide composites, changes during sintering affect how the material sticks together, the amount of air pockets, and the formation of cracks from shrinking. In Inconel alloys, heating and cooling processes can change how elements separate and form small particles, sometimes creating new types of phases that weren't the desired result of the treatment. Table 1 summarizes these relationships. It is structured based on material features and how important they are for engineering, instead of giving a general ranking of performance. These relationships form the starting point for the manufacturing changes that will be discussed in the next section. For CMCs, the main goal is to make sure the desired structure of reinforcement, interphase, and matrix is the same throughout the whole part. For Inconel alloys, the goal is to manage solidification and heat treatment processes to achieve the needed chemical composition and phase structure. In both situations, the quality of the product depends on the structure of the material and its proven performance.

Table 1. Constituent systems, microstructural design variables, and processing-sensitive behavior of selected CMCs and Inconel alloys.

Material system	Principal structural constituents	Central design mechanism	Important processing-	Engineering implication	References

			sensitive features		
SiC/SiC with BN-based interphases	SiC fibers, engineered interphase, SiC-based matrix	Load transfer combined with controlled debonding and crack redirection	Interphase thickness, layer arrangement, matrix condition	Interphase optimization requires balancing strength and damage accommodation	[9,10,14]
Architected C/SiC	Carbon fibers, SiC-based matrix, interphase	Architecture-dependent reinforcement and damage response	Inter-bundle and inter-fiber porosity	Textile architecture and infiltration quality must be evaluated together	[12]
Alumina/alumina oxide CMC	Alumina fibers and porous alumina matrix	Crack accommodation through a porous matrix	Sintering shrinkage, matrix cohesion, fiber preservation	Higher density alone is not a sufficient indicator of improved performance	[13]
Inconel 718	γ matrix, γ'' and γ' precipitates, δ phase and carbides	Precipitation strengthening with processing-dependent phase balance	Nb segregation and phase fractions after solution treatment and aging	Properties must be associated with a defined thermal and manufacturing history	[15,16]
Inconel 625	Alloyed γ matrix; secondary phases may form during thermal exposure	Primarily solid-solution strengthening	Nb/Mo enrichment and δ -phase precipitation	Stress relief and homogenization require control of phase evolution	[17,18]
Inconel 939	γ matrix with γ' strengthening developed through thermal processing	Precipitation strengthening	As-built dendritic structure and subsequent precipitate formation	Alloy chemistry alone does not establish the final strengthening condition	[19]

3. Recent Developments in Ceramic Matrix Composites

Recent progress in ceramic matrix composites is focusing more on how the different parts—like the reinforcement, the interphase, the matrix formation, and the shape of the components—work together. The goal of the research is not just about improving the individual features of the materials; it also focuses on keeping those features intact during the manufacturing process and creating a composite structure that works well even when exposed to mechanical and environmental stresses. Some recent improvements include designs that handle peeling and sliding separately, methods that mix materials together, ways to make parts with long fibers, and tests that show how damage happens inside the material.

3.1. Advances in Fibers and Interphase Engineering

3.1.1. Integrating fiber selection with composite architecture

Choosing the right fibers depends on the type of material they are used in and how the fibers are arranged within that material. A fiber that works well on its own doesn't always mean it will perform well in the final composite material. Bhatt and Halbig [20] showed this difference by doing tensile-creep tests on woven and layered melt-infiltrated SiC/SiC composites that used either Sylramic-iBN or Hi-Nicalon-S fibers. The tests included pressures from 48 to 138 MPa and temperatures as high as 1400 degrees Celsius in the air. Under the tested conditions, the slow deformation called creep in the woven composites was mainly controlled by the SiC matrix made through the CVI process, while in the laminated Hi-Nicalon-S composites, the creep was more influenced by the fiber behavior. So, the main part that is in control changes depending on the structure made from different materials [20]. This means that the process of making the reinforcing parts and the surrounding material should happen at the same time. Improving the ability of fibers to resist slow stretching will give the biggest advantage when the fibers' stretching plays a big role in how the composite material behaves. When the matrix behavior is the main factor, changing the matrix or how it works with the reinforcement might be a better solution. This understanding suggests that testing should be done for each part of the system and then checked to make sure it works correctly in the overall structure.

3.1.2. Separating interfacial debonding from frictional load transfer

Interphase engineering is becoming better at separating the resistance to initial debonding from the frictional resistance that happens after separation. These processes serve different functions. Debonding can change the path of a crack in the matrix and help keep the fiber safe, and the resistance from sliding afterward helps move the load and absorb energy. Hong et al. studied this difference by using bio-inspired porous pyro carbon layers in single-tow carbon/silicon carbide composites. The suggested design used some low-level separation along with a lot of friction once the parts were no longer stuck together. The authors said their material had a tensile strength of 903 MPa, which is about 38% higher than the regular design they compared it to, and also had 1.8 times more fracture energy. These results show that strength and energy absorption both improve at the mini-composite level [21]. The importance of this method is in managing the different stages of damage at the interface, instead of just changing a single overall bond strength value. When translating this material into bigger textile composites, it will be necessary to check if the same shape and mechanical behavior of the interface can be kept in tightly packed fiber groups.

3.1.3. Multilayer interphases for coupled mechanical and environmental performance

Multilayer interphases offer another way to give different roles to nearby material areas. Their development aims to bring together crack deflection, load transfer, and protection of the reinforcement all in one interphase system. A study from 2026 about BN/SiC dual-layer interphases looked at how the thickness of the SiC layer affected tensile properties in a high-temperature oxidative setting [14]. This method looks at how the interphase behaves while considering environmental damage, unlike approaches that only use results from the first mechanical test. This suggests that interphase design is moving towards conditions that are connected to service performance. Along with the research on porous interphases, these advances show that the structure of the interphase is becoming a way to control the order in which damage occurs. The response should involve redirecting the crack without losing the load too early, and then having the energy spread out steadily while the reinforcement keeps holding the load.

3.2. Matrix Densification and Hybrid Manufacturing Routes

3.2.1. Combining chemical vapor infiltration with polymer infiltration and pyrolysis

Hybrid processing mixes different manufacturing steps that each do a separate job in making the composite. In the CVI-PIP process, chemical vapor infiltration creates a first layer of silicon carbide around a coated reinforcement, and then polymer infiltration and pyrolysis add more material to the matrix. A study tested SiC/BN/SiC composites by first applying a CVI-SiC protective layer and then repeating the process of soaking in a chemical precursor and heating it to high temperatures [22]. The investigators used micromechanical techniques to study how the material behaved mechanically. This method is helpful because improving the bulk strength alone doesn't show where the real change happened—whether it was in the fibers, the layer between them, or the surrounding material [22]. Another study looked at one-way SiC/SiC composites made using a mix of CVI and PIP methods, with pyrolysis done at 1100, 1300, and 1500 degrees Celsius [23]. The study looked at the structure, how the material works mechanically at normal and high temperatures, how much it expands when heated, and how well it conducts heat. The way the experiment was set up shows that pyrolysis temperature needs to be checked against different performance needs, not just based on one strength test [23]. So, the real benefit of using hybrid processing is that it allows more flexibility in building the matrix around a system that has already been carefully designed. To get the best results, you need to pay attention to the sequence of steps, the state of the protective layers, and the structure formed by the heat cycles that come after.

3.2.2. Controlling residual phases in melt-infiltrated composites

Melt infiltration creates a structure where some leftover materials are still present, and these need to be taken into account when evaluating how well the material works at very high temperatures. Having some leftover silicon can affect how things interact with fibers and their coatings. In the systems studied by Bhatt and Halbig [20], when the temperature was higher than 1350 °C, it caused reactions between the leftover silicon, the fibers, and the coatings on the fibers. These reactions led to early failure due to creep rupture. This finding is specific to the materials and conditions tested, and it doesn't set a general temperature limit for all melt-infiltrated composites [20]. This evidence shows that there's a bigger goal than just lowering porosity: the amount and how these leftover materials are spread out need to work well with the heat the part will experience. So, matrix characterization needs to find areas that are chemically different and also measure how dense they are.

3.2.3. Accelerating thermal processing

Manufacturing productivity has also led to the use of different heating methods. Chen et al [24] suggested using joule heating to create both the fiber interphase and the matrix in SiC/SiC composites. The study takes the process development further by looking at how thermal energy is provided, not just focusing on the chemical makeup of the materials or the order in which they are introduced. The importance of these methods in aerospace relies on keeping things consistent while making the process faster. For complex parts, the evaluation should take into account how temperature changes in different areas, how the material transforms locally, how the layer between materials stays intact, and whether the parts can be made consistently. These are the standards used to evaluate whether something can be scaled up; simply having a successful quick test does not mean it can be made on a large scale in industry.

3.3. Three-Dimensional Architectures and Complex Component Manufacturing

A key progress is the expansion of CMC processing to more complex structures, where the placement of reinforcement needs to handle curved shapes, varying thicknesses, and different directions of force. The shape of the component affects both its structure and how it becomes denser: the preform needs to create the right paths for carrying loads, but it also has to be easy for the process that forms the matrix to work with. X. Liu et al [25] looked into SiC/SiC and C/SiC turbine blisks that had a biomimetic spider-web design and were at least 20 mm thick [25]. The production process used both CVI and PIP methods, and micro-computed tomography was employed to check the internal structure and how pores were spread out. The work also involved testing with over-rotation, which expanded the findings beyond just material samples to a larger rotating structure model [25]. The main contribution of this study is combining the design, building, checking inside, and testing of the structure. Nevertheless, over-rotation testing looks at a specific type of loading situation. Creating an aerospace service envelope also needs proof of the right thermal gradients, environmental conditions, repeated stress, and how parts are attached. For future component development, the important question is how to make and check a particular load-bearing structure throughout the part. Geometric complexity is useful in engineering when it helps create a structure that can be made again and works as expected.

3.4. Emerging Additive and Hybrid Manufacturing Approaches

3.4.1. Additive placement of continuous reinforcement

Additive manufacturing of CMCs includes various methods that are quite different in terms of materials used. Printing a ceramic shape, putting a mix of chopped fibers, and adding long fibers don't create the same kind of strong structure. The key progress for these continuous-fiber composites is being able to plan where the fibers go along with how the surrounding material is made. Liu et al [26] described a method that uses continuous-fiber additive manufacturing, followed by precursor infiltration and pyrolysis, and then liquid-phase silicon infiltration to make continuous SiC fiber-reinforced SiC composites. The process shows that additive manufacturing can create the first structure, and later steps build up the ceramic matrix [26]. Therefore, the final product should be explained by showing all the steps it went through during processing. Calling a composite just "3D printed" leaves out the steps involving heat change and material spreading, which are important for figuring out its different parts, air spaces, and how it reacts when touched.

3.4.2. Reinforcement across deposited layers

Layer by layer building brings up another important design question: how does the weight move from one area to the next? This issue becomes especially important when the fibers are mostly arranged in the same plane as where they are deposited. In 2024, a study looked at continuous carbon-fiber-reinforced silicon carbide and found that using vertical fiber placement along with material-extrusion printing helped fix the weak areas between layers [27]. This method considers how reinforcement is arranged across different layers as something that can be designed, instead of only depending on the bonding between areas of the deposited matrix [27]. This direction is important for aerospace structures in areas where there are both in-plane and through-thickness loads. However, the advantage should be considered along with how the placement of fiber affects local packing, infiltration, and the precision of dimensions.

3.5. Defect Control, Characterization, and Manufacturing Repeatability

Recent methods for studying materials are more often linking what is seen inside the material when it is damaged with how it behaves mechanically when tested. This is especially helpful for making products because the same big features can come from different inside designs. Guo et al [28] used four-dimensional in-situ X-ray microtomography, deep-learning-based image segmentation, digital volume correlation, and a CT-informed shear-lag model to study how SiC/SiC mini-composites behave when pulled apart by tension. The combined method connected how internal damage develops with the stress–strain behavior.[28] These methods help create a feedback system in manufacturing: they check the internal parts, see how they affect damage, and then change the production process to control the most important features. Their main contribution is not just better imaging, but a stronger link between the choices made during manufacturing and the resulting mechanical effects. For making sure things work well when making products, the right proof should show differences inside a part and also between different groups made in the factory. A good result from one sample shows that it's possible; consistent patterns of important qualities are necessary to help design the parts.

Table 2. Selected recent developments in ceramic matrix composites and their engineering significance.

Development	Material and approach	Reported evidence	Aerospace relevance and next validation step	Reference
Architecture-dependent creep assessment	Woven and laminated melt-infiltrated SiC/SiC	The constituent controlling creep differed between the investigated architectures	Coordinate fiber and matrix selection with the intended architecture	[20]
Porous interphase design	Single-tow C/SiC with porous PyC	Simultaneous improvement in tensile strength and fracture energy	Evaluate interphase uniformity and durability in larger textile composites	[21]
Hybrid matrix formation	SiC/BN/SiC produced by CVI followed by PIP	Micromechanical investigation of the resulting composite	Link constituent-scale changes to component-scale properties	[22]

Thermal-cycle optimization	Unidirectional CVI–PIP SiC/SiC	Comparison of three pyrolysis temperatures and multiple properties	Select processing conditions against combined mechanical and thermal requirements	[23]
Rapid heating-assisted fabrication	Joule-heating-assisted interphase and matrix preparation	Demonstration of an alternative thermal-processing route	Establish temperature uniformity and batch repeatability during scale-up	[24]
Thick structural demonstrators	Architected SiC/SiC and C/SiC blisks	Fabrication, internal tomography, and over-rotation testing	Extend structural evidence to representative coupled service conditions	[25]
Continuous-fiber additive manufacturing	SiC/SiC produced through additive placement, PIP, and silicon infiltration	Demonstration of a combined architecture-forming and densification route	Quantify orientation effects and defects throughout complex geometries	[26]
Reinforcement between printed layers	C/SiC with vertical fiber laying	Manufacturing strategy addressing interlayer weakness	Assess multiaxial loading and infiltration around cross-layer reinforcement	[27]
Image-informed damage analysis	SiC/SiC mini-composites under tension	Combined in-situ imaging, segmentation, correlation, and modeling	Connect measurable manufacturing features to damage initiation and progression	[28]

3.6. Integrated Development Pathway

The developments reviewed above support an iterative relationship between architecture design, fabrication, characterization, and structural testing. Figure 1 summarizes this relationship. The three processing branches represent alternative development routes; the appropriate route depends on the reinforcement system and component requirements. The architecture and processing methods are chosen based on the component needs, and then they are checked using microstructural analysis and tests that represent real-world conditions. The feedback loop shows the process of improving the design, not an automatic way to approve it. A method created by the author that combines the research methods talked about in this section. The main progress is the increasing ability to link a specially designed material property with how it affects how the material deforms and gets damaged. The way different phases are arranged can affect how they separate and move past each other; combining different processing steps can spread out the functions of the matrix material across several steps; and placing materials in specific areas can add strength to

certain parts. Their success in integration will rely on keeping these features the same as production goes from small samples to actual airplane parts.

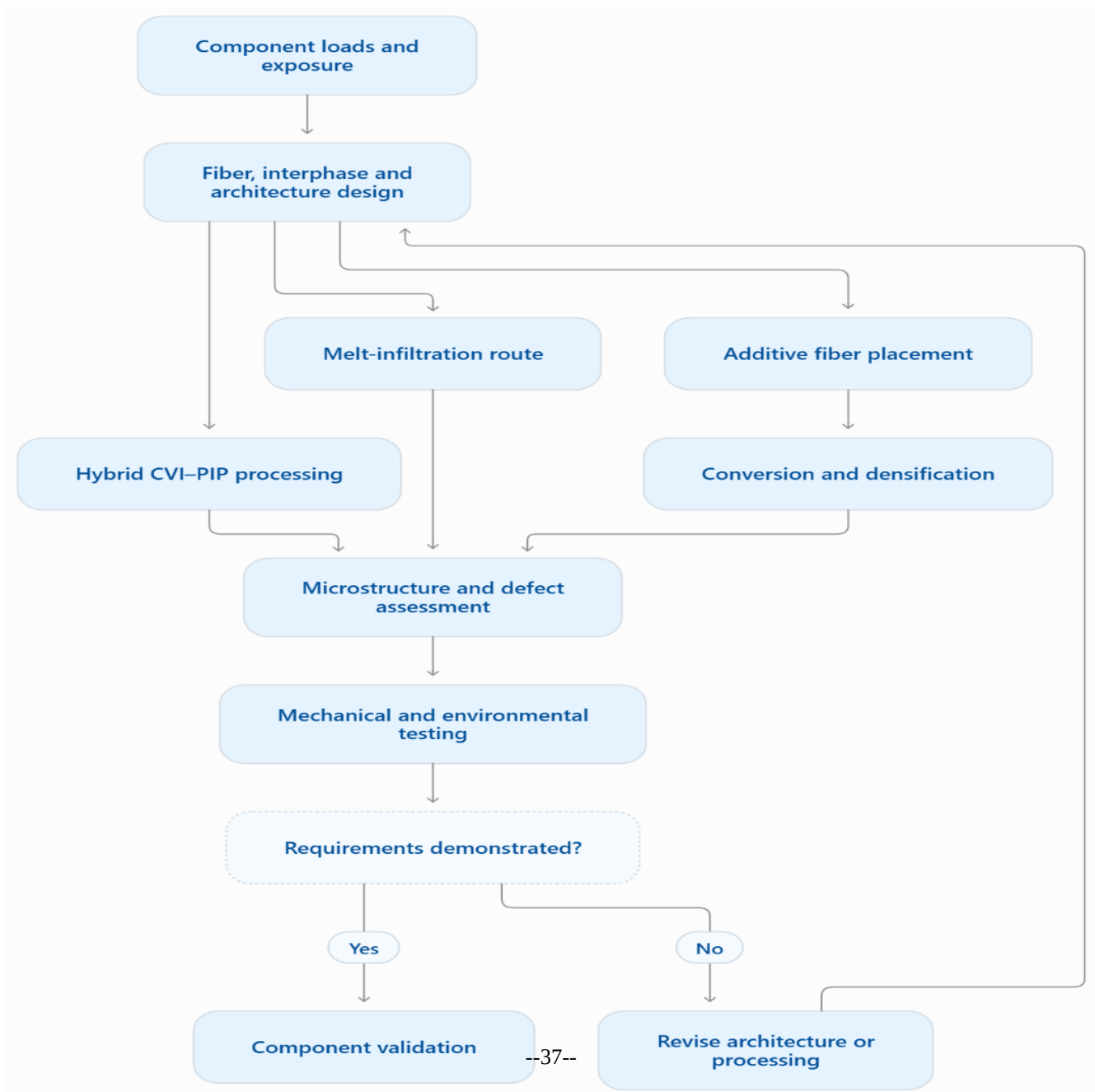


Figure 1. A combined approach for developing high-performance ceramic matrix composites.

4. Recent Developments in Inconel Superalloys

Recent advances in Inconel superalloys are making it more clear how choices made during manufacturing affect how well the parts work. Studies have grown from showing that an alloy can be made using a specific method to understanding how solidification, deformation, heat treatment, and surface preparation together influence strength, fatigue resistance, and how long the material lasts. This pattern is clearly seen in Inconel 718, but research on Inconel 625 and 939 shows that the methods used to process these materials need to be tailored to their specific chemical makeup and how they gain strength.

4.1. Advances in Conventional Processing

Traditional methods are still used to make things and they also serve as a standard for comparing new additive manufacturing techniques. Recent studies on powder consolidation show how deformation can help make the structure more uniform while dealing with features that come from the original powder material. Gaikwad and others [29] studied Inconel 718 made through powder forging and checked how it behaves mechanically at normal and higher temperatures. The treated material came close to being completely dense, broke apart the old connections between particles, and formed an even spread of hardening particles. The authors also said that the mechanical properties were almost the same in all directions under the conditions they studied. These results show that powder forging could be a good option when it's important to have even chemical makeup and consistent direction in the material [29]. This change is important because it does more than just pack a lot into a small space. Materials made from powder can keep some of the original surface features from the particles, and the process of joining them together needs to create strong bonds in those areas. Deformation-assisted processing allows for changing both the internal structure and the external shape. For making parts in the aerospace industry, you should pick between forging, casting, powder consolidation, and additive manufacturing based on what the part needs. Geometric complexity, direction of parts, how easy it is to inspect, how many are needed, and how long they need to last all play a role in making that choice. A processing method becomes useful when it can reliably create a consistent microstructure that fits the expected use conditions.

4.2. Additive Manufacturing of Inconel Components

4.2.1. From fabrication feasibility to performance optimization

Early studies on Inconel 718 made using a laser melting process showed that both the way it was made and the steps after making it could lead to good mechanical properties [7]. Recent studies have focused on understanding the different impacts of defects, material structure, and surface quality, instead of considering all additively manufactured materials as the same type [7]. In 2026, an experimental study described in Section 1 on purpose changed the settings for laser powder-

bed-fusion and heat treatments to create various types of defects and different material structures in Inconel 718 [8]. This kind of controlled comparison is important because two different processing conditions might result in the same overall density, but they can still have differences in the size, shape, position, and importance of the defects that remain [8]. So, the process improvement needs to be connected to the way things can go wrong. A condition that gives good tensile strength might not be the best for resisting fatigue if cracks start because of surface flaws or small defects inside the material.

4.2.2. Hybrid additive–subtractive manufacturing

Hybrid manufacturing combines the process of adding material with the process of shaping it during the creation of a part. This gives a chance to finish working on surfaces before later layers make it hard to reach them. Sommer et al [30] studied Inconel 718 made using laser powder-bed fusion, along with in-situ high-speed milling and later thermal treatments. In their samples, the average surface roughness went down from about 13.4 micrometers in the powder-bed-fused setup to 0.8 micrometers in the hybrid manufacturing method. The study also showed better mechanical performance because of the combined manufacturing process [30]. The engineering work involves adding surface control during the manufacturing process. When creating a complicated aerospace component, it's important to think about how to reach all parts for finishing during the planning phase, just like you would consider the way the part is built and how to take out the supports. The advantage of having more design flexibility is biggest when the shapes created can also work well for their intended purpose.

4.3. Solidification, Segregation, and Defect Formation

4.3.1. Local chemistry and phase development

Additive manufacturing exposes each new section of material to different processes of melting, cooling, and reheating. The local chemistry can be quite different from the overall composition, especially in areas that are not very reactive. In September 2026, a study used scanning and transmission electron microscopy, energy-dispersive spectroscopy, and JMatPro calculations to look at micro segregation in laser powder-bed-fused Inconel 718 [31]. The comparison showed that calculations using the nominal composition couldn't accurately show the highly segregated areas between the dendrites seen in the experiments [31]. This result means that when creating models for processes, we need to compare the predicted changes in phases with the actual measured compositions and structures at a small scale. Bulk-composition calculations are still helpful, but when we use them, we need to consider the different chemical makeup that happens during the manufacturing process. Evidence from Inconel 625, which was covered in Section 2, indicated that the buildup of niobium and molybdenum in certain areas sped up the formation of the δ phase during heating processes [17,18]. These studies together show that segregation is connected to how solidification happens and how the material responds to heat treatment later on.

4.3.2. Distinguishing defect reduction from microstructural optimization

Defect reduction and microstructural optimization are connected but different goals. Closing a pore alone doesn't create a good distribution of precipitates. Making stronger precipitates doesn't fix a surface notch. Processing methods need to take into account the characteristics that influence the desired mechanical behavior. A study looked at how Inconel 718, made using hot-isostatic pressing and laser powder-bed fusion, performed under high-cycle fatigue at 600 degrees Celsius [32]. The analysis looked at how cracks start after a lot of defects have been reduced, focusing on things like small movements in the material and how grains with different directions interact. This shows that the way damage is controlled can change when processing defects are minimized [32]. The idea is that as manufacturing quality gets better over time, you need to do more detailed testing and analysis. Once big defects are no longer the main issue, factors like the crystal direction, how much the material bends or stretches in certain areas, and how the different parts of the material are arranged can become more significant.

4.4. Heat Treatment and Hot Isostatic Pressing

4.4.1. Heat treatment as part of the manufacturing route

Heat treatment controls how the microstructure of a material changes from its original state to its final condition. For precipitation-strengthened Inconel alloys, it affects how the strengthening phases, segregated areas, and grain boundary components balance with each other. The study by Sommer et al [30] gives a good example of how static and cyclic performance are different from each other. Direct aging made the ultimate tensile strength of their powder-bed-fused parts stronger, but it didn't make the endurance limit any better than when the parts were first made. Their treatment based on HIP created a different mix of tensile and fatigue properties. In that experiment, the processing condition that gave the highest tensile strength wasn't necessarily the one that performed best in terms of fatigue. Heat treatment selection should start with the needed combination of properties. Strength, flexibility, ability to withstand repeated stress, consistency in shape, and performance under high heat should all be considered together, not treated as separate goals to be optimized individually.

4.4.2. Extending post-processing strategies to Inconel 939

Inconel 939 needs special care because its γ' -strengthened structure is different from the structure of Inconel 718. Schedules set up for one grade should not be used just because both materials are part of the Inconel family. In 2025, a study looked at cast and laser-made Inconel 939 parts after they were heated and pressed with high pressure and heat. It looked at the microstructure and mechanical properties, including how well it performs under creep conditions, by comparing it to the material that was cast using standard methods. This method links additive processing to a known material state while keeping the original structures separate. The bigger change is moving towards post-processing that is made for a certain type of metal and the original structure it starts with. Hip, solution treatment, and aging should be seen as steps that affect each other, and the order in which they are done needs to be proven through experiments.

4.5. Surface Integrity, Machining, and Repair

4.5.1. Surface preparation as a structural requirement

Surface condition influences both the buildup of stress in a specific area and the start of damage. For additively manufactured parts, finishing becomes a structural concern instead of just a matter of size or appearance. The results from the hybrid manufacturing process mentioned earlier show how important it is to manage surfaces during the making of a product [30]. However, surface roughness alone isn't enough to fully explain the condition of a finished part. Inspection should also look at problems close to the surface, damage caused by machining, leftover stress, and the shape of parts that take a lot of stress. These factors link the finish requirements to how well the parts work.

4.5.2. Directed energy deposition for local restoration

Directed energy deposition allows material to be added to specific areas of an already made part. To fix something with this method, you need to manage the material that's added, the area that gets hot because of the heat, and how the new material connects with the original surface. Cano-Salinas et al [34] created a simulation where they added material into prepared features on the substrate to fix Inconel 718. Their investigation combined choosing the right process and parameters with using a microscope and measuring hardness at different scales in the area that was repaired. When tested under these conditions, the repairs had strong metal bonds and no cracks or areas where the metal didn't fully join. The deposit had a greater hardness than the base material [34]. These findings show that it's possible to create the fake object, but they also explain why checking for differences in the repaired area is necessary. A fixed part has material that has gone through different heating and shaping steps, even if the base material and the added material are both called the same type of alloy.

4.5.3. Fatigue performance of repaired joints

Mechanical validation needs to check the repaired joint directly. Sarkar et al [35] checked how well Inconel 718 repairs worked when the fatigue load was applied at a right angle to the boundary between the base material and the weld. They compared directly aged and solution-treated-and-aged conditions. The material that was deposited had tensile strength similar to the original metal, but the fixed joints had lower resistance to fatigue when subjected to many cycles of stress. The way the two heat treatments performed compared to each other changed depending on the amount of stress applied [35]. A study from 2026 looked more closely at how long repaired parts last when made with laser-directed-energy-deposition, using both experiments and a type of computer model that looks at how crystals in materials behave under stress [36]. The study connected fatigue behavior with the different phase structures and areas of high stress in the repaired material [36]. These results show a clear path for improving repairs: it's important to show strong local bonding, but the repaired structure also needs to have a proper and consistent response to repeated cycles of use. Repairing the geometry, applying heat treatment, and checking the state of the leftover material all need to be part of the same production process. The changes discussed here show that the final Inconel part can be considered the result of a full manufacturing process. Consolidation or depositing creates the first shape; heating changes the material's phases and any flaws; shaping finishes the useful parts of the product; and testing checks if everything works as it should. This relationship forms the foundation for comparing how high temperatures cause damage in the next section.

Table 3. Selected recent developments in Inconel processing and their implications for aerospace components.

Development	Alloy and processing route	Evidence or principal finding	Engineering implication	Reference
Deformation-assisted powder consolidation	Powder-forged Inconel 718	Near-full density, disrupted prior-particle-boundary networks, and approximately isotropic properties in the tested conditions	Provides a route for controlling both consolidation and microstructural uniformity	[29]
Integrated deposition and finishing	Inconel 718; powder-bed fusion with in-situ milling	Improved surface condition and mechanical performance	Finishing access can be incorporated into build planning	[30]
Locally informed phase analysis	Laser powder-bed-fused Inconel 718	Nominal-composition calculations did not directly reproduce strongly segregated regions	Thermodynamic predictions should be checked against local chemical measurements	[31]
Fatigue assessment after defect reduction	HIP-treated, powder-bed-fused Inconel 718	Investigation of fatigue mechanisms at 600 °C	Microstructural crack initiation remains relevant after reducing porosity	[32]
Grade-specific post-processing	Cast and powder-bed-fused Inconel 939	Comparative assessment of heat treatment, HIP, microstructure, and mechanical response	Treatment schedules should reflect alloy chemistry and starting structure	[33]
Local material restoration	Laser-metal-deposited Inconel 718	Repair-interface characterization and successful bonding in the investigated specimens	Establishes process feasibility, followed by a need for structural validation	[34]
Joint-level fatigue testing	DED-repaired Inconel 718	Comparable deposit tensile strength did not ensure equivalent joint fatigue performance	Test the complete repair region under relevant loading	[35]
Analysis of fatigue variability	LDED-repaired Inconel 718	Experimental and modeling investigation of phase-related stress concentrations	Qualification should address scatter as well as average performance	[36]

LPBF: laser powder-bed fusion; DED: directed energy deposition; LDED: laser directed energy deposition; HIP: hot isostatic pressing. The studies use different specimen geometries and test conditions and do not constitute a direct ranking of processing routes.

5. High-Temperature Performance and Damage Mechanisms

High-temperature performance depends on how a material changes when it faces mechanical stress, heat, and environmental factors all at the same time. For aerospace components, the initial strength is just one part of how they respond. If you keep applying a load for a long time, it can cause slow stretching or deformation. If you apply the same load many times, it can weaken the material over time. And if the material is exposed to harsh or reactive environments, it can change how it breaks or cracks. These processes can affect each other, so the order and how long each condition is applied can impact how long a part lasts. Ceramic matrix composites and Inconel superalloys handle these conditions in different ways. In continuous-fiber CMCs, matrix cracking, interfacial sliding, and fiber bridging can help spread the load around before the material finally breaks. In Inconel alloys, how the material bends without breaking, how small particles stay in place, how the edges between grains act, and what happens at the tip of a crack all play a big role in how the material behaves mechanically. So, when they compare things, they need to look at both what is being measured and the actual process or reason behind it.

5.1. Mechanical Properties and Temperature-Dependent Behavior

5.1.1. Strength, stiffness, and damage initiation

For CMCs, the start of matrix cracking and the maximum tensile strength show different stages of how the material deforms. A composite can still hold up well even if cracks form in the matrix because the undamaged fibers keep supporting the broken areas. Even though matrix cracking changes how stiff something is, moves stress around, and can let in environmental stuff. The observations made directly during the experiment in Section 1 showed that internal damage can be fixed when the material is subjected to high temperatures [3]. These measurements help tell the difference between gradual damage and the final break and give a better way to understand how material behaves under stress [3]. For Inconel alloys, properties like yield strength, maximum strength, how much it stretches before breaking, and how it responds to repeated stress all show different parts of how well it works. The results from Section 4 showed that making the material stronger by heating it did not always lead to better resistance against fatigue in the tested Inconel 718 samples [30]. So, neither the strength to stretch nor the hardness by itself can fully show how long a structure will last [30]. So, a comparison based on components should find out which event is important: the first permanent change in shape, the start of cracks in the matrix, a big drop in stiffness that's not acceptable, the cracks spreading, or the end when it finally breaks. These events do not have to happen at the same level of maximum strength in both types of materials.

5.1.2. Comparing performance at relevant temperatures

When comparing temperatures, it's important to clearly show the temperature of the surrounding gas, the coating, and the material that holds the load. A high-temperature material test also needs to be understood along with how long it lasts, the force applied, and the surrounding environment. For example, studies on woven CVI- and PIP-treated SiC/SiC materials looked at how they stretch and deform over time at high temperatures up to 1650 degrees Celsius in air [37]. These tests show how much a material can bend or break under certain conditions; however, the highest temperature

reached in the tests isn't the same as the maximum temperature it can safely handle over time. When choosing materials, the right way to compare them is based on how well they can handle a specific mix of temperature, stress, time of exposure, and the amount of damage that's allowed. Looking at maximum temperatures alone doesn't show how different parts of aerospace systems work and how they are cooled.

5.2. Creep and Stress Rupture

5.2.1. Constituent-dependent creep in CMCs

Creep is time-dependent deformation under sustained loading. In a composite, the measured strain shows how the different parts work together and how the load moves between them. Bhatt and Halbig [20] showed that the part of the material responsible for slow stretching, known as creep, was different between the woven and the layered types of SiC/SiC systems they studied. Their work also found big differences in how ruptures happen, which is connected to small variations in the structure of the material. These results explain why you can't predict composite creep just by looking at the fiber properties alone [20]. The research looked at how CVI- and PIP-made SiC/SiC materials perform up to 1650 degrees Celsius. It also checked how different batches behave, the ways they bend or break, the reasons they fail, and how well they keep their strength after being exposed to long-term heat stress [37]. It's important to include properties that are still present because a sample that passes a sustained-load test might still have hidden damage that could affect how it works later [37]. So, helpful ways to describe creep include looking at how much the material stretches over time, how long it takes to break, what kind of damage happens, and how well it still works after that. The importance of these measurements depends on what kind of problem the part is having, like whether it's bending too much, leaking, losing space between parts, or breaking.

5.2.2. Microstructural control of time-dependent damage in Inconel

In Inconel alloys, the ability to resist slow deformation over time is influenced by how the main material, the strengthening particles, and the grain boundaries work together. The material chosen for high tensile strength might need more improvement if continuous loading causes a lot of damage. A 2026 study on laser powder-bed-fused Inconel 718 showed that adding short periods of tension during thermomechanical fatigue testing greatly decreased the material's lifespan. The authors linked the response to not enough grain boundary precipitation, which might help sliding and cracking between grains [38]. This interpretation highlights that where the precipitate forms and the overall strengthening conditions both affect how performance changes over time [38]. The real goal is to have a microstructure that works well with the planned way the material will be used. A treatment that works best for a single cycle or a fixed test isn't necessarily the best choice for long periods of time at high temperatures.

5.3. Fatigue and Thermomechanical Fatigue

5.3.1. Environment-sensitive fatigue of CMCs

Fatigue in CMCs can include things like repeated cracking in the matrix, sliding at the interfaces, changes in how stress is distributed across the fibers, and gradual damage to the reinforcement. When the temperature is high, the air around can change how fast and in what order these processes happen. Ruggles-Wrenn and others [39] tested three different SiC/SiC systems at 1200 degrees Celsius in both air and steam. Steam significantly lowered the fatigue performance in the studied

traditional CVI and melt-infiltrated systems, but it had a much smaller effect on the composite with an oxidation-inhibited matrix. The study set the run-out at 2×10^5 cycles and checked the tensile properties that were still present in the specimens that survived [39]. The result shows that just saying "SiC/SiC" isn't enough to know how well a material will hold up against fatigue in a combustion environment. The way the chemicals in the matrix interact and how the layers between them are designed can affect how sensitive the whole material is to its environment. Run-out also requires careful interpretation. It shows that the material can survive a certain number of cycles under the test conditions; it doesn't mean it will last forever or keep all its original properties.

5.3.2. Thermal–mechanical phase relationships

Thermomechanical fatigue occurs when temperature and mechanical strain vary during the same cycle. The phase relationship matters: in an in-phase cycle, maximum tensile mechanical strain coincides with maximum temperature, whereas an out-of-phase cycle places maximum tensile mechanical strain near minimum temperature. Guth et al [38]. tested post-processed, laser powder-bed-fused Inconel 718 between 300 and 650°C under both phase relationships. Without dwell periods, its lifetimes approached those of conventionally rolled material. Adding ten-minute tensile dwells at 650 °C markedly reduced the performance of the tested additive condition. Thus, agreement under one waveform did not establish equivalence under another [38] . For aerospace assessment, cycle frequency, strain range, temperature range, dwell duration, and phase relationship should therefore accompany fatigue results. These parameters determine how much opportunity exists for time-dependent deformation and environmental damage during each cycle.

5.3.3. Dwell-sensitive crack growth

Research on dwell fatigue in Inconel 718 has looked at how factors like grain size, temperature, time under load, and the surrounding environment affect how cracks spread [40,41]. In 2017, an investigation included the effects of oxygen at the tip of a crack into a model that explains how cracks grow over time and at different temperatures [41]. This kind of work helps to consider environmental exposure as a key factor in how fatigue develops [40, 41]. These observations also show why just counting the number of cycles might not be enough. Two histories with the same number of cycles can cause different amounts of damage if the time spent at each stage or the conditions, they are exposed to are not the same.

5.4. Fracture and Damage Tolerance

5.4.1. Distributed damage in ceramic composites

Damage tolerance in a continuous-fiber CMC comes partly from its ability to spread the load around the cracks in the matrix. Interfacial debonding, crack deflection, bridging, and frictional sliding can help use up energy before the fiber actually breaks. The 2026 study on porous-interphase, covered in Section 3, showed that single-tow C/SiC samples had better tensile strength and fracture energy at the same time [21]. Its relevance is the on-purpose separation of the first debonding from the later frictional load transfer [21]. However, distributed damage should not be mixed up with having no effect on the structure. Matrix cracks can make the material less stiff and allow areas inside that were once protected to become exposed. A good response to damage needs both strong structure and the ability of the damaged material to handle ongoing exposure to the environment.

5.4.2. Crack initiation and propagation in Inconel

For Inconel parts, damage tolerance means being able to tell the difference between when a crack first starts and when it grows later. Problems in making the product, the shape of the surface, and small details in the material can lead to the start of a crack. Sarkar et al [35] on repairing joints shows an important point: even if the strength of the material being added is similar to the original metal, the whole joint might not perform as well when it comes to fatigue [35]. The assessment needs to link where the crack probably started with the condition of the nearby material. A repair area, a machined surface, or a specific section of material might need different testing compared to the normal main material.

5.5. Oxidation, Hot Corrosion, and Environmental Degradation

5.5.1. Internal environmental attack in SiC-based composites

Environmental damage to SiC-based CMCs goes beyond just what happens on the outside surface. The interphase and reinforcement can be seen when connected pores, matrix cracks, or other open paths allow them to be exposed. Detwiler and Opila [42] looked at how SiC/BN/SiC oxidizes when exposed to dry oxygen and a mix of water vapor and oxygen, at temperatures ranging from 400 to 800 degrees Celsius. Their work shows how important it is to look at exposure at intermediate temperatures as well as the highest temperatures the system is meant to handle. Environmental durability can't be fully explained by just testing the highest temperature [42]. The results about steam fatigue mentioned earlier also show that environmental resistance relies on the whole composite system [39]. So, when checking how well something can still hold up under weight, you need to look at both mechanical cracking and chemical exposure at the same time.

5.5.2. Distinguishing oxidation from deposit-assisted hot corrosion

For Inconel alloys, oxidation and hot corrosion are two different types of exposure conditions. Hot corrosion tests create deposits that can change how protective reaction layers form and stay stable. Muthu et al [43] tested both wrought and direct-metal-laser-sintered alloy 718 at 800 degrees Celsius. They exposed the materials to air and salt-filled environments for 120 hours in a repeating cycle. The experiment set up a way to separate air oxidation from situations where the substance was mixed with sulfate, chloride, and vanadium. These tests show how behavior changes with specific deposit chemistry. Their results should be connected to the real pollutants and heat levels that a part might face. Neither being resistant to clean-air oxidation nor having good short-term mechanical properties on their own means a material is protected from attack caused by deposits.

5.6. Coupled Damage and Lifetime Assessment

The previous evidence shows that high-temperature damage happens as a series of connected events. A mechanical crack can make it easier for the environment to affect the material; a chemical attack can make the connection between parts or the edges of the material weaker; continuing stress can then make the material bend or break faster. Which interaction is most important depends on the material's structure, its tiny internal features, and how it has been used over time. For engineering evaluation, this means moving from individual parts to groups that show how things work together. First tests check how materials behave under tension, slow stretching over time, repeated stress, and different environmental conditions separately. Further tests show which combinations are important for the part, like tension and fatigue during repeated loading, exposure to steam while the part is being used repeatedly, or heating and cooling after the part has already been damaged. The main link is between how damage happens and what the service needs to do. CMC development needs to keep the load transfer working well even as mechanical and environmental damage happens over time. Inconel development has to maintain the right structure inside the material, the right kind of particles, the condition at the grain boundaries, and the surface quality throughout the whole process of applying load. Protective coatings play a key role in this response and are discussed in the next section.

Table 4. Comparison of high-temperature damage mechanisms and assessment priorities for CMCs and Inconel superalloys.

Damage process	CMC response of interest	Inconel response of interest	Measurements needed for meaningful assessment
Initial mechanical damage	Matrix cracking, interfacial debonding, and stiffness change	Yielding and localized plastic deformation	Full stress–strain response, loading direction, temperature, and damage observations
Sustained loading	Constituent creep, load redistribution, and fiber rupture	Time-dependent deformation and grain-boundary damage	Strain–time history, rupture time, microstructure, and retained properties
Cyclic loading	Sliding, progressive cracking, and reinforcement degradation	Crack initiation and fatigue-crack propagation	Stress or strain ratio, frequency, waveform, surface condition, and run-out definition
Thermomechanical cycling	Architecture-dependent response to combined thermal and mechanical loading	Phase-dependent cyclic deformation and creep–fatigue interaction	Temperature–strain phase relationship, ramp rates, and dwell periods
Environmental exposure	Interphase and fiber attack through accessible pathways	Oxidation and environmentally assisted cracking	Atmosphere, pressure, exposure duration, and cross-sectional damage

Deposit-assisted degradation	System-specific coating and substrate reactions	Salt-dependent hot corrosion	Deposit composition, loading, replenishment, and temperature
Accumulated damage	Residual stiffness and remaining fiber-supported strength	Remaining crack-growth resistance and load-bearing section	Post-exposure testing linked to the preceding loading history

6. Protective Coatings and Interface Engineering

Protective coatings are a key part of the materials used in aerospace parts that work in high-temperature environments. Their role goes beyond just covering a surface: they control how heat moves, protect against environmental damage, allow for expansion and contraction due to temperature and mechanical stress, and affect where and how damage develops. How well a coating works depends on how its materials, the way they are arranged at a tiny level, the places where they meet, and the base material they are applied to, all interact with each other. For silicon carbide-based ceramic matrix composites, environmental barrier coatings are used mainly to deal with damage caused by harsh combustion conditions. For Inconel parts that need heat protection, thermal barrier coatings (TBCs) offer a ceramic insulation layer that is attached using a suitable bonding method. These functions can overlap, but environmental resistance and thermal insulation are still separate design needs.

6.1. Environmental Barrier Coatings for Ceramic Matrix Composites

6.1.1. Rare-earth silicates and environmental protection

Rare-earth silicates are key materials for helping to shield SiC-based composites. Ytterbium disilicate, $\text{Yb}_2\text{Si}_2\text{O}_7$, and ytterbium monosilicate, Yb_2SiO_5 , have been studied a lot because their chemical properties and how they work with other materials can be changed by adjusting the type and structure of the coating they have. Resistance to one type of exposure doesn't mean you're resistant to all situations involving fire or burning. A study compared plasma-sprayed ytterbium monosilicate and disilicate coatings to see how they reacted to calcium-rich and calcium-poor calcium–magnesium–aluminosilicate deposits [44]. This method understands that the makeup of minerals swallowed can change depending on the experiment, not that it's a fixed part of what is called "CMAS" [44]. So, when choosing the right EBC, you need to look at things like how much water vapor it will see, the type of deposits it might get, the temperature it will handle, and the mechanical stresses it will face. A coating composition needs to work well with both the bond coat and the main material it's applied to.

6.1.2. Deposition-controlled microstructure

The layer put on a part may be different from the original material in terms of how it is arranged, how much empty space it has, and its specific structure in different areas. These features affect how chemicals move and how things react when they get hot. Owusu et al looked at ytterbium disilicate coatings that were made using suspension plasma spraying, and they studied how these coatings performed when exposed to steam and CMAS. Tests were done at 1350 degrees Celsius for 96 hours to compare steam velocities of 1 and 5 meters per second. The slower speed caused silica to turn into gas, but the faster speed led to both silica turning into gas and the material

wearing away. The results show that changing the speed of the gas can affect how the material breaks down, even if the temperature and how long it's exposed stay the same [45]. This means that the performance of EBC cannot be explained just by looking at the coating material or a single oxidation test. Deposition parameters set up the starting shape, and the exposure conditions control how that shape changes over time.

6.2. Thermal Barrier and Oxidation-Resistant Systems for Inconel

6.2.1. Thermal insulation and bond-coat function

A typical metallic TBC system has a ceramic top layer, a metal bonding layer, and the superalloy base material. In systems that use a bond coat containing aluminum, a layer of alumina-rich thermally grown oxide can form when the system is exposed to heat. The ceramic layer helps block heat, and the bond coat helps stick things together and keeps them safe from the environment. These functions must be considered separately. An insulating coating does not eliminate the temperature-related restrictions of the base alloy. The thermal advantage is based on the heat flow, the thickness of the coating, how well it conducts heat, and how effectively the part can remove heat. Prabhu and others [46] looked at how an air-plasma-sprayed NiCr/YSZ coating system on Inconel 718 handles repeated oxidation. Their study showed that thermal cycling causes microcracks and faster oxidation, showing that a coating's starting condition doesn't mean it will stay stable after being exposed many times [46].

6.2.2. Multilayer ceramic topcoats

Multiple layers of topcoat let different ceramics add different useful qualities. Instead of having one layer handle all the thermal, mechanical, and chemical needs, the design spreads out these functions among neighboring layers. Rajasekaramoorthy et al [47] looked at different types of coatings, including YSZ, gadolinium zirconate, a bilayer made of YSZ and GZ, and functionally graded coatings, all applied on NiCrAlY-coated Inconel 718. Their investigation used high-temperature X-ray diffraction along with tests for oxidation, thermal cycling, and thermal shock. Among the tested setups, the bilayer system gave a better overall result in those tests[47]. This result shows that architecture-based optimization works well, but it still focuses on the specific systems used and the test conditions applied. It does not prove that all multilayer or graded coatings will work better than a single-layer coating.

6.3. Coating–Substrate Compatibility and Residual Stresses

6.3.1. Thermal expansion and strain accommodation

Adjacent coating layers generally undergo different unconstrained thermal strains during heating and cooling. When bonded together, these differences generate stresses whose magnitude depends on thermal expansion, elastic response, geometry, temperature gradients, and the ability to relax strain.

A useful first-order description of the mismatch strain is:

$$\Delta\varepsilon_{th} = \int_{T_0}^T [\alpha_c(T) - \alpha_s(T)] dT,$$

where α_{c} and α_{s} are the thermal expansion coefficients of the coating and the substrate. This

phrase talks about a mismatch in strain; to figure out the coating stress, you also need to know the material's mechanical properties and the conditions at the edges. Rajasekaramoorthy et al. [47] shows how important it is to measure how materials expand when heated along with how their structure changes. Choosing the right coating needs more than just picking a material that doesn't conduct heat well [47].

6.3.2. Substrate chemistry and buried-interface evolution

Chemical compatibility is equally important. Elements from the surface layer can influence the chemicals formed at hidden areas and thus change how long the coating lasts. Ardrey et al [5] looked at environmental barrier systems used on solid SiC materials and SiC-based composites. They linked changes in how the thermally grown oxide behaves to the chemistry of the substrate, such as the movement of boron from the composite into the silica layer. This shows that a coating tested on a simple model material might act differently when used on the actual CMC [5]. The main idea is to look at the coating and the material it's applied to as a single system that works together. A good topcoat can't fix a weak bond coat or a changing chemical interface on its own.

6.4. Coating Degradation and Failure Mechanisms

6.4.1. Thermal cycling and interfacial damage

Repeated heating and cooling can cause or make existing cracks in the coating layers and at the places where different parts meet. At the same time, oxidation and changes in the material's phase affect the structure in the area where the cracks spread. When looking at metallic TBCs, checking all three layers—the thermally grown oxide, the bond coat, and the ceramic layer—together helps tell the difference between damage caused by oxidation and failure that happens mainly because of thermal mismatch. For EBCs, attention needs to be given at the topcoat–bond-coat and bond-coat–substrate areas. The study on Inconel 718's cyclic oxidation shows that thermal cycling and oxidation can happen at the same time [46]. So, isothermal exposure and thermal cycling should be seen as two different but related tests, not as tests that can be used instead of each other when checking how durable something is [46].

6.4.2. CMAS infiltration and reaction

Molten CMAS can get into the coating's features that are easy to reach and then react with the materials in the coating. The resulting products might either stop more damage or keep causing more harm. Their effect is influenced by how fast reactions happen, what the deposited material is made of, and whether the reaction layer stays connected. The experiments that compare yttrium silicates with various CMAS mixtures [44] deal with a key part of assessing coatings: the environmental conditions must be clearly defined chemically. A result from one man-made deposit shouldn't be applied to all types of sand or ash that someone might swallow.

6.4.3. Combined steam–CMAS exposure

When different exposures happen together, they can lead to behaviors that aren't seen when each exposure is tested alone. Lynam et al studied yttrium disilicate coatings that had about 8%, 15%, and 22% pores. They tested these coatings under steam, CMAS, and a mix of steam and CMAS at a high temperature of 1350 degrees Celsius for 100 hours. When both conditions were considered together, the CMAS penetration went up by about 25% compared to when only CMAS was used. The reaction products also changed, and yttrium aluminum garnet appeared. Porosity had a small

effect on how well the material resisted corrosion within the studied range [48]. These results indicate that porosity or resistance in just one environment alone does not fully explain how well this coating system works. Combined testing is especially useful when the main use involves checking for both water vapor and mineral buildup.

6.5. Emerging Multilayer and Multifunctional Coatings

6.5.1. Compositionally complex environmental barriers

Multicomponent rare-earth silicates offer more options for designing EBCs. Their value should be determined by testing how stable they are during phases, how they react, and how well they work with other things, not just by looking at how complicated their makeup is.

A 2026 investigation examined the CMAS response of the high-entropy disilicate $(\text{Yb}_{0.2}\text{Y}_{0.2}\text{Lu}_{0.2}\text{Er}_{0.2}\text{Dy}_{0.2})_2\text{Si}_2\text{O}_7$.

When exposed to 1500 °C, an apatite-like layer formed that slowed down the glass from moving through compared to the other materials mentioned in the study [49]. The result shows that changing the chemical structure can help control how coatings react with deposits [49]. Showing that a material is resistant to corrosion is different from showing that a coating applied to a surface lasts a long time. We also need to check how the material behaves when deposited, how well it sticks, how it handles temperature changes, and if it works well with real CMC systems.

6.5.2. Abradability and environmental resistance

Abradable coatings add another mechanical role: they allow for controlled material to be removed when the coating comes into contact with a moving blade tip. Their design needs environmental protection along with the right kind of wear response. The study on abradable EBC by Lynam et al.[48] shows that it's important to check how this multi-purpose design works when exposed to different chemicals at the same time. Corrosion can change the material, and this change might affect how it wears down or gets rubbed over time [48]. The development goal is therefore a fair approach across all areas. Trying to make one thing like hardness, density, or chemical resistance better on its own might not give the best abradable system. The coating design needs to satisfy three key needs: it must protect against the environment it's meant for, work well with the material during temperature changes, and be possible to make on the part it's being applied to. New research supports this link by looking at combined exposures and how hidden layers change over time. These points help in choosing full material systems for the aerospace uses that will be talked about next.

Table 5. Representative coating systems and recent developments relevant to CMCs and Inconel substrates.

Coating system	Principal function	Evidence discussed	Design implication	Reference
Plasma-sprayed ytterbium monosilicate and disilicate	Environmental protection	Comparison against calcium-rich and calcium-lean CMAS	Deposit composition must be specified during evaluation	[44]
Suspension-plasma-sprayed ytterbium disilicate	Steam and deposit resistance	Steam velocity altered the observed	Include relevant flow conditions alongside	[45]

		degradation processes	temperature and duration	
NiCr/YSZ on Inconel 718	Thermal protection with a bonding layer	Cyclic exposure involved microcracking and accelerated oxidation	Assess thermal cycling and chemical damage together	[46]
NiCrAlY with YSZ/GZ architectures on Inconel 718	Thermal protection and strain accommodation	Bilayer configuration performed favorably in the investigated tests	Optimize layer arrangement as well as composition	[47]
Abradable ytterbium disilicate	Environmental protection and controlled wear	Combined steam–CMAS exposure increased penetration	Validate chemical durability under combined exposures	[48]
Multicomponent rare-earth disilicate	Candidate CMAS-resistant material	Formation of a penetration-limiting reaction layer at 1500 °C	Extend material-level results to deposited coating systems	[49]
Rare-earth silicate/Si systems on SiC-based substrates	Protection through a compatible coating stack	Substrate chemistry affected oxide-scale evolution	Use representative substrates when assessing durability	[5]

YSZ: yttria-stabilized zirconia; GZ: gadolinium zirconate; CMAS: calcium–magnesium–aluminosilicate. The table summarizes different experimental systems and does not imply equivalent technology readiness.

7. Aerospace Applications and Component-Level Material Selection

The aerospace importance of ceramic matrix composites (CMCs) and Inconel superalloys comes from how well they work as full components, including coatings, cooling channels, connections, and ways to attach parts. Choosing the right material needs more than just looking at things like how heavy it is, how strong it is when stretched, or the highest temperature it can handle. The important thing to consider is if a specific material system can handle the needed loads and conditions over time, while also following the rules for making it, checking it, and keeping it in good shape. The developments discussed in this chapter back three different ways to use these materials: adding CMCs to specific high-heat parts, making Inconel parts better with new manufacturing methods and controlling their structure, and combining various materials in one part. These strategies have different levels of maturity. Commercial production, testing of individual parts, and lab-based feasibility studies should stay as separate areas when evaluating how much technology has advanced.

7.1. Aero-Engine Hot-Section Components

7.1.1. Stationary CMC components

Stationary turbine parts show a clear example of how CMC materials are used in aerospace engineering. GE shipped its 100,000th CMC turbine shroud for the CFM LEAP engine, which started being used in commercial flights in 2016 [50]. This manufacturing achievement shows that a certain component design is being used in industry; it doesn't mean every CMC mix or engine use has the same level of development [50]. GE is working on developing parts for the GE9X combustor and turbine, which shows how CMC materials are being used in more areas than just shrouds. In its 2015 report, the document talked about testing engines that were being demonstrated and listed parts like the inner and outer combustor liners, the first and second stage high-pressure turbine nozzles, and the first-stage shrouds as components that were planned to use CMC materials [51]. In this context, turbine nozzle refers to a fixed blade assembly, not a rocket engine exhaust nozzle [51]. When choosing materials for these parts, it's important to think about how the composite material works with its protective coating system. As talked about in Section 6, the condition of the environmental barrier coating determines how much of the underlying SiC-based material is exposed to combustion products. Component assessment should therefore look at coating damage, local temperature differences, the forces holding parts together, and the effects of cracks in the material. A helpful way to think about the design is to compare the temperature of the gas stream with the temperature of the material that supports the load. Cooling, coating properties, and heat transfer affect the latter. So, a measured engine gas temperature can't be used as the actual temperature that the CMC material or another metal alloy is constantly exposed to.

7.1.2. Rotating CMC components

The extension of CMC technology to rotating hardware requires separate evidence. A 2026 study reported fabrication of ultrathick SiC/SiC and C/SiC turbine blisks using a biomimetic architecture and combined chemical vapor infiltration and polymer infiltration–pyrolysis processing [25]. This work addresses an important manufacturing challenge: producing thick, geometrically complex composite structures. It should be interpreted as experimental component development rather than evidence of commercial rotating-component qualification [25]. For selection purposes, successful fabrication is only one assessment stage. A rotating component also requires evidence concerning load transfer through its architecture, geometric stress concentrations, manufacturing variability, environmental exposure, and damage progression under repeated operation. Results from stationary shrouds cannot establish these capabilities automatically.

7.1.3. The continuing role of Inconel

Inconel is a group of alloys that each have different ways to make them strong and are used for different purposes. Special Metals includes alloys like 617, 625, 706, 718, and X-750 in its aerospace offerings [52]. Choosing between them needs evidence that is specific to the alloy, not just a general set of properties for all nickel-based superalloys. The studies on processing and damage covered in Sections 4 and 5 also show why it's important for application decisions to clearly state the material condition. Just knowing the name "Inconel 718" isn't enough to tell you about how the part was built, if it was heat treated, its surface state, how much stress is left in it, or if it was fixed or repaired before. These variables are especially important when looking at how traditional products compare to those made or fixed using additive manufacturing methods. So, the right way to compare is between two properly set up component setups: one is a specific CMC structure along with its coating and added parts, and the other is a specific Inconel alloy along with how it was made, how it was cooled, and how its surface is protected.

7.2. Rocket Propulsion Components

Rocket engines show how choosing the right materials and managing heat are both important, along with how they are made. Gradl and Protz looked into advanced methods for making regeneratively cooled channel-wall nozzles, such as directed energy deposition and laser-wire direct closeout. Their research looked at Inconel 625 along with other possible alloys and covered making the materials, checking their properties, and testing them with hot fires [53]. These results show examples of specific manufacturing methods at the component level, not a general approval for all additively manufactured Inconel parts [53]. The advantage of using additive manufacturing here is closely tied to the shape of the component. Internal passages and structural finishes need to meet all three requirements at the same time: thermal performance, keeping pressure contained, and being able to be made through manufacturing processes. A good material choice relies on how well the channel-wall structure is made and the results from testing separate samples. Multi-material construction provides another route. NASA's RAMPT project looked into mixing GRCo copper alloys with Inconel 625 or NASA HR-1 using different additive manufacturing methods. The program also looked into making and testing chambers and nozzles together in a realistic rocket setup [54]. This method gives each material in the assembly a separate job [54]. For a proper comparison, the extra interfaces need to be looked at carefully. A combination of different materials needs to be checked for how well they stick together, how consistently they can be made, how they might bend or change shape when exposed to heat, and how easy it is to examine them. The possible benefit of using different materials together needs to be considered in relation to the requirements for combining them. CMC-based propulsion concepts need a similar evaluation that focuses on each individual part. Evidence from a cut piece or a combined sample alone cannot prove that a pressure-holding propulsion part is durable. When looking at these results, the test setup, how the structure was loaded, and what it's meant to be used for again should all be clear and easy to see.

7.3. Thermal Protection and High-Temperature Flight Structures

Thermal protection applications require a different balance of needs compared to those that apply to long-term turbine operation. Candidate materials can face strong temporary heating, oxidation, surface wear, and many times going through heating and cooling cycles. The evaluation needs to tell the difference between surviving the exposure and still having the structure's ability working after that. Ge et al studied the cyclic removal of C/SiC–ZrC composites that were made using a method that combines deposition with infiltration and pyrolysis processes [55]. Their observations showed that a surface oxide layer made of SiO₂ and ZrO₂ formed, showing how changing surface chemistry is important during exposure. These results are about the material that was studied and the conditions used in the experiment; they don't mean the material is ready for use in flight [55,65-68]. When choosing materials, the results from ablation should be considered together with the exposure history and the condition after exposure. A low recession rate by itself isn't enough to ensure good remaining strength, steady size, or the ability to be used again. Comparing different studies needs clear and matching descriptions of heat flux, atmosphere, time of exposure, and how the test samples were set up. This difference is especially important when talking about "ultrahigh-temperature capability." A brief time at a high surface temperature is very different from running continuously at that temperature while carrying a load. The chapter therefore looks at ablation resistance, environmental durability, and structural service capability as connected but different qualities [69-74].

7.4. Joining and Integration of Dissimilar Materials

Joining links the creation of materials to the making of real aerospace parts. A good composite or superalloy might not help much if it creates too much stress, stops the material from moving when it gets hot, or makes it hard to check for problems. A recent example that relates directly to this chapter is the 2025 study on brazing C/C–SiC to Inconel using a Ticusil filler [56]. The research looked at how interfaces change, the strength of the joined parts, and the leftover stresses, showing that whether a join works depends on both the chemical reactions happening and how well the materials can physically fit together. The creation of reaction products at the interfaces makes the joint act like a separate material with its own characteristics [56]. Two important differences are key when understanding these studies. Brazing temperature is a manufacturing parameter, not a proven continuous service limit. Second, the initial strength of the joint doesn't show how well it will hold up when faced with temperature changes, ongoing pressure, and being exposed to different environments. For developing components, the evidence should move from looking at the structure and early strength to testing under real loading and exposure conditions. The assessment should also find out where the failure happens: inside the composite material, in the filler, along the reaction layer, or in the metal base. Similar measured strengths can hide very different ways of failing and different effects on checking.

7.5. Comparative Case Studies and a Material-Selection Framework

Table 6 compares representative applications according to the evidence available, rather than assigning a universal ranking to either material family.

Evidence categories describe the examples that are cited; they are not official technology-readiness ratings.

A practical selection procedure follows five stages [75-80]:

1. Define the duty. Specify the thermal exposure, mechanical loading, environment, required life, and allowable damage.
2. Define the material system. Include the processing history, fiber architecture when relevant, coatings, joints, and cooling methods.
3. Screen against failure mechanisms. Use the methods from Sections 5 and 6 to find out the important limiting conditions.
4. Compare complete components. Check the total weight of the installed parts, how many units are made successfully, how easy it is to inspect, what options are available for fixing issues, and the total cost over the product's lifetime.
5. Match the evidence to the decision. Tell apart coupon testing, subpart checks, showing a typical part, and real-world use.

This framework is a combination of the earlier evidence in engineering terms. It helps make decisions that are specific to each application, but it stops people from taking good lab results and

using them to say the service works well in general. It also sets out the requirements for the methods used in modeling, inspecting, and qualifying, which are discussed in the next section.

Table 6. Application-specific opportunities and evidence boundaries for advanced CMCs and Inconel-based systems.

Application	Material or architecture	Reported evidence	Principal selection question
Commercial turbine shrouds	SiC-based CMC system	LEAP production and revenue-service application [50]	Can the complete coated component meet the required life and maintenance targets?
Combustor liners and stationary turbine nozzles	CMC hot-section components	GE9X-related demonstrator testing and development [51]	Are thermal gradients, environmental exposure, and attachments adequately addressed?
Experimental turbine blisks	SiC/SiC and C/SiC	Complex, thick-component fabrication study [25]	Does the architecture retain acceptable capability under representative rotating loads?
Regeneratively cooled rocket nozzles	Inconel 625 among investigated alloys	Manufacturing development and hot-fire testing [53]	Are channel-wall integrity and cyclic durability reproducible?
Integrated rocket assemblies	Copper alloy–superalloy combinations	NASA multi-material manufacturing and test development [54]	Do interface performance and thermal compatibility support the intended duty?
Thermal-protection candidates	C/SiC–ZrC	Laboratory cyclic-ablation evidence [55]	What structural capability remains after the required exposure history?
Composite–metal joints	C/C–SiC joined to Inconel	Brazing, interface, and residual-stress investigation [56]	Does the joint remain durable and inspectable under service conditions?

8. Modeling, Nondestructive Evaluation, and Qualification

Using advanced ceramic matrix composites and Inconel superalloys effectively needs a link between how they are made, how they behave structurally, how damage can be measured, and whether the part is acceptable. Modeling shows how the structure of a material affects how it works; nondestructive evaluation gives details about the material's condition as it's made and changes over time; qualification checks if the final part meets what it was supposed to do. These activities work best when done together. Recent research shows how these methods work together by using images to create combined models, simulating how materials deform in 3D-printed Inconel, and using machine learning to understand signs of damage. The engineering worth of something depends on if the predictions stay accurate under different material conditions, shapes, and environments that are important for the intended use [28].

8.1. Multiscale Modeling of Ceramic Matrix Composites

CMC models need to show how damage happens at different levels of the structure. The way the fibers and matrix share the load and how they separate at the interface happen in small areas, but the way the fibers are arranged, the parts of the material that have more matrix, and the presence of air pockets affect how the material bends or stretches in bigger areas. Component analysis needs

to turn these mechanisms into forecasts about how stiff something will be, how stress will change, and how damage will form. In 2024, a study used four-dimensional in-situ micro-computed tomography, digital volume correlation, and a CT-based shear-lag model to analyze SiC-fiber/SiC mini-composites. Three-dimensional images taken one after another showed how damage happened when the material was stretched, and the spacing between cracks in the matrix helped create a better mechanical model. This method links internal observations to the expected stress–strain behavior instead of only using an externally measured load–displacement curve [28]. The difference between adjusting model parameters and checking if the model works well is key to understanding this type of work. When crack spacing is measured and given to a model, it matches the mechanical response, showing it aligns with what is observed. Predicting how cracks will form in a separate test piece, under specific loading conditions, or in a different structure is its own separate check.

For developing components, a helpful way to organize the model is by using a hierarchy.

- Small-scale models that look at how fibers, the surrounding material, and the area between them behave.
- Mesoscale models show the shape of the tow, how porous the material is in certain areas, and how different types of damage affect each other.
- Component-scale models take into account thermal gradients, attachments, geometric changes, and how structural loads are redistributed.

This hierarchy is an engineering system, not a rule that every part has to use all three levels directly. The complexity of the model should be chosen based on the decision it is helping to make and the data that is available to check how well it works.

8.2. High-Temperature and Environment-Sensitive Validation

Testing a model at normal room temperature alone isn't enough to know if it will work well in high-temperature environments. Temperature changes affect how materials behave and cause thermal strain, and the surrounding air can lead to wear and damage that wouldn't happen in an experiment where the environment is completely inert and has no effect. In 2026, a study looked at C/SiC composites by using in-situ X-ray microtomography and digital volume correlation while applying tensile forces at room temperature and 1200 degrees Celsius. The investigation looked at how the material deformed from inside and tracked how damage developed over time, going beyond just what was seen on the surface. These measurements give spatial data that can be used to check how well predictions about where strain will concentrate and how damage will form are accurate [57]. For the model, temperature, how long the exposure is, and the atmosphere should all be considered separate inputs. Signing a contract for a high-temperature tensile test doesn't mean it proves anything about oxidation rates or how materials behave over a long time under heat. Just like that, being able to recreate the final breaking force doesn't mean the model accurately predicts all the earlier damage steps. A program that checks things in a component-based way needs to look at several important factors: how stiff the whole part is, how much stress is in different areas, where the damage is happening, how the damage is spreading, and how well the part can still carry weight after damage occurs. Agreement on these measurements gives more solid proof than agreeing with just one number.

8.3. Microstructure-Sensitive Modeling of Inconel Superalloys

For Inconel alloys, predictive modeling needs to link the manufacturing method and the resulting microstructure with how the material deforms plastically and experiences fatigue. This requirement is especially important for additive manufacturing, because the crystal structure direction and any flaws can change based on how the process is done. In 2024, a study looked at how Inconel 718 made through wire-arc additive manufacturing behaves under low-cycle fatigue. They used a model called crystal-plasticity that took into account the crystal directions and any flaws in the material, and they checked their results with real experiments [58]. The study shows how details about the material's internal structure can be used in analyzing fatigue, instead of just using a general relationship between stress and strain. The usefulness of this model depends on how its material and loading conditions are defined. Parameters made for one way of depositing material shouldn't be used directly for another method, different heat treatment, or other surface conditions. Validation done under isothermal cycling alone doesn't show how well something works when it goes through thermomechanical fatigue with dwell periods. For engineering use, simulations that consider the microstructure are especially helpful when they show a clear difference in results based on how something is made. A model that shows how a defect population or orientation distribution affects local deformation can help make better processing decisions. Using it for checking how long parts last also needs estimates of how sure we can be and checks done on their own in proper situations.

8.4. Nondestructive Evaluation and Damage Monitoring

Inspection methods need to be chosen based on the type of damage and the decision that needs to be made. Manufacturing acceptance, laboratory damage characterization, and in-service monitoring all have different goals, even though they may use similar sensing technologies. X-ray tomography and digital volume correlation give different but useful information: tomography shows the inside structure, and correlation between images helps measure how parts move and stretch inside. Recent studies in CMC have shown that using these things together helps understand where damage starts and how it changes how deformation moves [57,58]. The ability to see a feature clearly in a lab sample does not automatically mean it can be found reliably in a bigger part that has a different shape and is harder to reach. Acoustic emission provides another way to see damage happening as it occurs. Muir et al used acoustic-emission measurements, X-ray computed tomography, and an autoencoder-based analysis to study how damage develops in unidirectional SiC/SiC composites when they are subjected to steady tension [59]. Connecting sound signals to actual damage seen on its own isn't enough to know exactly what caused the damage. That's why it's helpful to link the sounds with what's actually observed.

Table 7. Relationships between modeling, measurement, and validation in advanced CMC and Inconel development[57-59].

Approach	Information obtained	Engineering use	Validation question
CT-informed CMC mechanical modeling	Internal architecture, cracking, and associated mechanical response	Relate observed damage to stiffness and load transfer	Can the model predict an independent specimen or loading condition?
High-temperature CT with digital volume correlation	Internal deformation and damage during heated loading	Assess predicted strain localization and damage progression	Are temperature, atmosphere, and exposure duration representative?

Crystal-plasticity modeling of AM Inconel	Microstructure-dependent plastic deformation and fatigue indicators	Compare orientation and defect effects	Does validation cover the actual processing and material condition?
Acoustic emission combined with CT	Time-resolved signals linked to observed damage	Develop damage-identification methods	Do classifications remain valid across specimens and sensor configurations?
Manufacturing and inspection records	Traceable processing and acceptance evidence	Support reproducibility and component disposition	Are process changes controlled and inspection capabilities demonstrated?

8.5. Machine Learning, Data Integrity, and Predictive Uncertainty

Machine learning can help with dividing data into groups, understanding signals, and making predictions in a smart and fast way. Muir et al [60] showed a multimodal approach, which is a clear example: they linked acoustic-emission analysis with observations of physical damage. Using this method in real engineering situations needs to check how well it works with different materials and various ways of measuring, not just by splitting the signals randomly from the same test. For future programs that develop models, the training and testing should be done separately at the stage that is important for when the model will be used. If the goal is to predict something about a new manufactured part, testing with separate builds or samples gives better results than just removing certain image parts or sound clips from a shared experiment. Uncertainty should also be divided into its main causes. Measurement uncertainty deals with how accurate the observations are; material variability refers to differences between samples that are supposed to be the same; parameter uncertainty is about how well the model is calibrated; and model discrepancy is about things the math in the model doesn't account for. Reporting these contributions helps decide if more testing, better understanding, or changing the model would most improve the prediction. A digital twin needs these elements to be linked to the changing state of a specific part. A static simulation or a trained surrogate by itself doesn't create that link. For the systems we are looking at, a good goal is to update the estimates of component states using information from the manufacturing and inspection processes, and also keep clear limits on how confident we are in the predictions.

8.6. Qualification and the Transition to Component Acceptance

The qualification should show that it can be reproduced and also work well. A successful test shows that a certain setup works; for it to be accepted in production, you also need to make sure the conditions that made the test work are under control. NASA-STD-6030 gives a good guide for making spaceflight parts using additive manufacturing, including how to design, build, and test them [60]. NASA's explanation says that an additive manufacturing control plan and a quality management system are key parts of the framework. Its scope is different from the process used to certify civil aircraft and from the process used to qualify CMCs [60]. Equipment and facility control are handled separately according to NASA-STD-6033 [61]. This separation shows that checking the material properties and testing the parts needs to be done with a controlled production setup [61]. For both CMC and Inconel development, this sequence shows the key evidence needed to move forward with accepting a component: The main point is that proof of qualification has to

stay connected to a specific material and manufacturing method. Any changes in how the fiber is structured, covered, processed with additives, heated, fixed during repairs, or checked should be looked at to see how they affect the existing evidence. This link between process control and actual performance helps improve modeling and characterization, which supports making aerospace hardware more reliable and consistent.

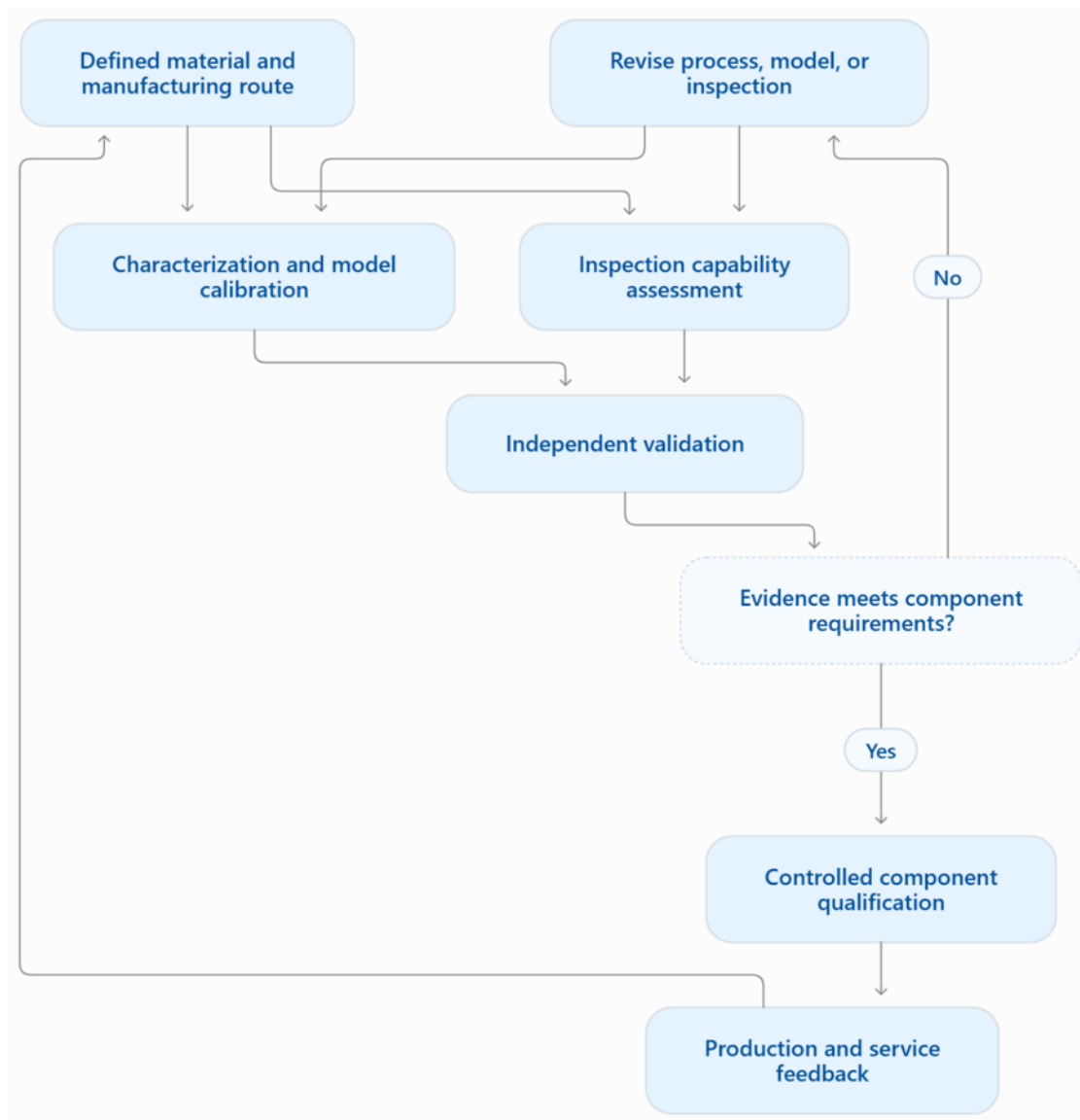


Figure 2. Proposed integration of manufacturing control, predictive modeling, inspection, and component qualification. The diagram is an engineering synthesis, not a prescribed certification procedure

9. Industrial Challenges and Future Research Directions

The next step in developing advanced ceramic matrix composites and Inconel superalloys is about turning better materials into parts that work reliably every time. Higher temperature capability, less weight, and more flexibility in making parts are still key goals, but their usefulness in industry depends on how well they can be made, how long they last, how easy they are to check for problems, how cheap they are to fix, and overall cost over the time they are used. The research goals coming from the earlier sections focus on bringing together materials, how things are made, and how structures are designed.

9.1. Manufacturing Scalability and Process Reproducibility

For CMCs, making them in a factory needs to take into account how the material's properties are spread out in space, as well as the overall density or strength of the material. Local differences in how water gets into the soil, how the material is pulled or dragged, and how much empty space is left can cause some areas to act differently than what is seen in smaller test samples. When you want to make a successful process work on a bigger or more complicated part, you need to manage how materials move and how chemical reactions happen throughout the whole structure. Shinde et al. created a model for making C/SiC composites using chemical vapor infiltration. This model connects how gas moves in the reactor with how it travels through the porous material before the composite is formed [62]. The predictions were checked against actual measurements of total density and how much empty space was left after the process. This work shows how connecting reactor conditions to the internal state of the made composite is better than just trying to improve processing time without considering how evenly the material is packed [62]. A real-world research goal is to find out the time periods during which the process works well even when the shape of the starting material and its initial air pockets vary in real situations. Future manufacturing research should therefore include information about how properties are spread out in space, how consistent results are between different batches, and what percentage of parts meet the required standards. These steps would make faster processing options more helpful when comparing industries. For Inconel made through additive manufacturing, managing the feedstock is a good example of how reproducibility depends on the process used. Keller et al. looked at how well Inconel 718 powder could be reused in different ways—some with adding new powder and some without—over 54 times [63]. They noticed some changes in the powder properties but did not see any major decrease in the material's ability to withstand fatigue under the conditions they tested. Their mechanical specimens were machined, which is important when interpreting the results for components that keep their original, as-built surfaces. The results show that recycling can be done in a controlled way within the process studied; however, they don't set a general limit on how many times something can be recycled.[63] The bigger point is that the history of manufacturing should be included in how we define materials. For CMCs, this involves the preform and densification process history; for Inconel, it includes the feedstock condition, build history, heat treatment, and finishing process. Industrial transfer becomes more dependable when these variables can be tracked and connected to proof of acceptance.

9.2. Durability Under Combined Service Conditions

When environmental and mechanical damage happen together during use, they should be checked at the same time. Separate tests for oxidation and fatigue are still helpful in understanding the reasons behind material failure, but the results from these tests alone may not always show how the material behaves when exposed to both issues at the same time. Bhatt et al. studied both coated and uncoated melt-infiltrated SiC/SiC composites that were subjected to sustained peak low-cycle

fatigue in steam at temperatures of 1204 and 1315 degrees Celsius [64]. Their observations linked coating damage to later moisture-related damage and crack growth in the composite. This shows that when evaluating how long something lasts, you need to look at both the coating and the material it's attached to, because they affect each other. Future tests should build on this method by looking at typical examples of how loads are applied and how materials are exposed. For example, if there is some damage to the coating before, it might affect how the material reacts to the environment later on. Also, if the material has been exposed to something before, it could change how it responds to mechanical stress later. Knowing how these events depend on each other can help create a more accurate evaluation of life than just looking at one exposure at a time. For Inconel parts, the main goal is to link the fatigue, creep, and environmental factors talked about in Section 5 with the real condition of the material. Additive manufacturing and repair can create different microstructures in various areas, so checking each part closely is especially important. Research programs should therefore link the places where damage starts with the history of how the product was made and any treatments after manufacturing, and then check if these connections still hold true when exposed to typical heat and movement conditions.

9.3. Higher-Temperature Coating Systems

Expanding the temperature capability of a CMC requires consistent advancements all through its defensive coating framework. A more hard-headed topcoat gives constrained advantage in the event that a fundamental layer gets to be the temperature-limiting constituent. Lee et al. tended to this challenge in a 2026 examination of natural obstruction coatings for SiC/SiC frameworks focusing on 1482 °C [65]. The consider inspected a mullite-based elective to ordinary silicon bond coats and assessed coating optimization through heater steam cycling and combustion-related rigs. Thermal-expansion compatibility and chemical intelligent between layers were central contemplations. The temperature expressed as an advancement target ought to be recognized from illustrated component benefit capability [65]. A beneficial investigate heading is hence the facilitated plan of substrate, bond coat, middle layers, and uncovered surface. Candidate frameworks ought to be compared utilizing reliable introduction conditions and disappointment definitions. Important results incorporate attachment maintenance, natural infiltration, reaction-layer improvement, and leftover substrate properties. The same component-level thinking applies to defensive coatings on Inconel. Coating improvement ought to build up how testimony and consequent presentation influence the fundamental combination, particularly where the substrate has experienced added substance fabricating or repair. Enhancements in surface security must stay consistent with the mechanical prerequisites of the total component.

9.4. Repairability and Life Extension

Repairability ought to be considered amid starting fabric and component choice. A fabric framework that performs well when recently made may require a diverse upkeep technique once harm has gathered. The Inconel repair ponders examined prior [34,35] give a premise for assessing deposition-based reclamation, but future work ought to put more noteworthy accentuation on already uncovered substrates. Repaired components contain both held fabric and recently presented fabric, at the side an interface and a modified thermal history. Evaluation ought to subsequently incorporate the condition of the initial substrate and the area of ensuing harm. For CMC frameworks, a critical inquire about qualification is between reestablishing natural assurance and reestablishing auxiliary capability. Supplanting a harmed coating does not itself illustrate recuperation of debased strands or interfacing. A valuable repair-development program would

combine pre-repair assessment, repair-process control, and post-repair introduction beneath agent stacking. Over both fabric families, the building objective may be a substantiated remaining-life evaluation. This requires prove connecting perceptible harm, repair limits, and consequent strength. Repeated-repair histories ought to too be explored where numerous support intercessions are aiming.

9.5. Economic and Environmental Assessment

Financial and natural comparisons ought to utilize a utilitarian premise that reflects the aviation application. Fetched per kilogram and fabricating vitality per component are enlightening, but they don't capture contrasts in benefit life, review, repair recurrence, or operational execution. A reasonable life-cycle comparison ought to account for raw-material generation, handling, rejected parts, wrapping up, coating, upkeep, and end-of-life treatment. Operational benefits ought to be included as it were when upheld by a fitting component or framework appraisal. In specific, a diminishment in component mass ought to not be changed over into a flying machine fuel-saving claim without considering its area, working profile, and framework integration. Powder reuse offers one opportunity to make strides asset productivity in Inconel fabricating, bolstered by the controlled-recycling prove examined over [64]. Its financial advantage by the by depends on the related characterization, taking care of, and acknowledgment necessities. For CMCs, handle advancements ought to so also be surveyed through vitality utilize and generation surrender nearby handling time. Future thinks about would be more comparable in case they detailed a clearly characterized utilitarian unit, such as a component assembly indicated execution prerequisites over a characterized benefit interim. Affectability examination ought to at that point build up how conclusions alter with power supply, fabricating surrender, support presumptions, and accomplished component life.

9.6. Research Priorities for Industrial Translation

The going before prove bolsters a investigate plan organized around quantifiable designing results. Table 8 presents proposed needs instead of estimates of commercial status. Three associated destinations rise from this system. To begin with, fabricating changes ought to create a repeatable fabric state. Moment, characterization and modeling ought to set up how that state advances amid benefit. Third, review and support ought to give usable criteria for tolerating, repairing, or resigning the component. For CMCs, these destinations coordinate consideration toward coordinates natural security, building consistency, and damage-aware auxiliary plan. For Inconel superalloys, they emphasize manufacturing-condition-specific execution, controlled fabric reuse, and substantiated repair. Advance in both areas will depend on illustrating that advancements survive the move from carefully characterized examples to reproducible aviation congregations.

Table 8. Research priorities for the industrial development of advanced CMCs and Inconel superalloys[55-60].

Priority	CMC research focus	Inconel research focus	Evidence needed to demonstrate progress
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Reproducible manufacturing	Control infiltration uniformity, architecture, and residual porosity	Control feedstock, build variability, heat treatment, and surface condition	Consistent properties and acceptance yield across independent batches
Combined-environment durability	Link coating damage, environmental ingress, and composite degradation	Resolve interactions among cyclic deformation, dwell loading, and environmental damage	Representative loading–exposure tests with identified failure mechanisms
Protective-system compatibility	Develop compatible higher-temperature coating stacks	Assess coating–substrate interactions for manufactured and repaired conditions	Retained protection and mechanical capability after exposure
Repair and maintenance	Distinguish coating restoration from structural recovery	Characterize retained substrate, deposited material, and repair interfaces	Validated repair limits and remaining-life assessments
Predictive methods	Connect architecture and internal damage to component behavior	Connect microstructure and defects to deformation and fatigue	Independent validation with quantified uncertainty
Inspection	Relate detectable indications to consequential damage	Link flaw populations and surface condition to component acceptance	Demonstrated detection capability in representative geometries
Resource efficiency	Reduce processing burden while maintaining yield and durability	Manage powder reuse and repair within controlled production routes	Life-cycle comparisons based on equivalent component function
Component integration	Validate attachments and composite–metal interfaces	Validate multi-material transitions and local thermal histories	Assembly-level performance under relevant thermal and mechanical loading

10. Conclusions

Improvements in ceramic matrix composites and Inconel superalloys between 2010 and 2026 have increased the options for making aerospace parts that work well in tough heat, pressure, and environment conditions. Their development goes in different but related ways: CMCs provide chances for lighter parts in high-temperature areas, while Inconel superalloys help make strong, complex parts using special alloy properties, well-known manufacturing methods, and better additive manufacturing and repair techniques. Their success relies on choosing and checking the whole material system for a specific part and the conditions it will work in. For CMCs, improvements in fiber structure, the way fibers and matrix interact, how to pack the material tightly, and protecting it from the environment have made it possible to use them in certain parts of stationary engines in industry. More growth needs careful management of the whole structure, differences in how parts are made, the strength of the coatings, and how well things stick together. Environmental barrier coatings are important for lasting strength because if they break down, it can cause the material underneath to suffer more damage from the environment faster. So, as things get better with the temperature that the base material can handle, the protective coating also needs to improve in a way that works well with those changes. Also, it needs to show that the material's

structure stays strong even when it's under different types of stress and environmental conditions at the same time. Additive manufacturing has given Inconel superalloys more design flexibility and allowed for new ways to combine parts and repair components. These benefits are closely connected to managing defects, crystallographic texture, residual stress, heat treatment, and surface condition. Having just an alloy designation is not enough to determine if products made through traditional methods, additive manufacturing, or repair processes perform the same way. Using leftover powder and repairing by depositing new material can help use resources better, but it's important to check how well these methods work in terms of strength over time, protection against damage from the environment, and how reliable they are for the specific job they're meant for. The comparison between these material families is most helpful when looking at individual parts. Density and temperature limits help narrow down choices at first, but the final decision needs to consider heat changes, cooling needs, how the material has been used before, the environment it will face, how easy it is to check for problems, and how much care it needs. Hybrid assemblies can give different tasks to different materials, but the places where they connect need to handle heat, sharing forces, and lasting longer. So, changing materials means you have to look at the whole assembly instead of just comparing the properties of individual materials. New advances in tomography, full-field deformation measurement, acoustic emission, and models that focus on microstructure are improving how well processing relates to how damage develops. These methods can help make better design choices if their predictions are checked on their own and their uncertainties are clearly explained. Machine learning can help make sense of complicated measurements, but its usefulness in engineering comes from using real-world data that is based on physical principles and proven to work across different materials, production settings, and real-life conditions. Qualification is still the key connection between these analytical improvements and dependable aerospace hardware. Future progress needs to be judged by how well the parts last, how consistently the products are made, and how clearly the long-term benefits are shown. For CMCs, the main focuses are protecting the environment, creating architectures that can be repeated reliably, and ensuring strong structural connections. For Inconel superalloys, the performance is controlled during manufacturing, repairs are done through validated methods, and the use of raw material is made as efficient as possible. Connecting materials development with manufacturing, inspection, and how long materials last gives the best way to create lighter, more efficient, and easier-to-maintain aerospace systems.

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CHAPTER 3

MECHANICAL AND TRIBOLOGICAL PERFORMANCE OF POLYMER-MATRIX COMPOSITES DEVELOPED WITH SUSTAINABLE AND WASTE-DERIVED FILLERS: A REVIEW OF CURRENT APPROACHES AND FUTURE PERSPECTIVES

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Abstract

Polymer-matrix composites hold an increasing share of contemporary engineering applications owing to their low density, ease of processing, and properties that can be tuned over a wide range through fillers. This review systematically examines, in the light of the current literature, the effects of mineral, ceramic, metallic, solid-lubricant, fibrous and especially waste-derived fillers—incorporated into thermoset, thermoplastic and elastomeric matrices—on the mechanical strength and friction-wear behaviour of the resulting composites, and it further covers emerging directions such as two-dimensional and nanoscale fillers, self-healing and

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adaptive composites, artificial-intelligence-driven tribo-informatics, green tribology and digital twins. A distinguishing feature of this work is that it treats mechanical and tribological performance not as separate criteria but as a dual-competence problem to be optimized jointly. The decisive role of the matrix–filler interface, tribological phenomena such as transfer-film and third-body formation, the value of sustainable fillers within a circular economy, and characterization and modelling approaches are discussed, and prospective research avenues are presented in a dedicated section. The reviewed studies indicate that, when filler type, loading, particle size and surface treatment are jointly optimized, waste- and bio-derived additives can compete with conventional fillers in both environmental and performance terms. Keywords: polymer-matrix composite, filler, tribology, wear, sustainability, tribo-informatics, self-healing composite, digital twin.

Introduction

Among engineering materials, polymer-matrix composites (PMCs) constitute a class distinguished by their high specific strength, corrosion resistance, vibration-damping capacity and freedom of manufacture relative to metals. Requirements that a neat polymer cannot meet on its own—hardness, stiffness, dimensional stability, thermal conductivity or wear resistance—can be tuned to a large extent through fillers incorporated into the matrix as a secondary phase. The type, volume fraction, particle size, geometry and dispersion of the filler, together with the quality of bonding at the matrix–filler interface, are the fundamental variables that govern the ultimate behaviour of the composite (Ge et al., 2026).

Research in this field has matured along several axes in recent years. On the one hand, in machine elements operating under friction and wear, polymer composites are replacing their metallic counterparts; in sliding bearings, bushings, gears and seal

applications, composites based on polyamide, polytetrafluoroethylene (PTFE) and polyoxymethylene (POM) are widely preferred (Ünal et al., 2023b; Ünal et al., 2025; Deshwal et al., 2024). On the other hand, driven by sustainability pressures, the valorization of agricultural, industrial and municipal wastes as fillers both reduces dependence on virgin raw materials and provides a value-added solution to waste management (Muthukutti et al., 2025; Kyriakidis et al., 2024). Beyond these, approaches such as two-dimensional materials and nanofillers, self-healing and adaptive systems, artificial-intelligence-assisted materials design and digital twins are transforming the field from a traditional trial-and-error paradigm towards a data- and function-oriented design philosophy (Yin et al., 2023; Cai et al., 2022; Inturi et al., 2024).

At the intersection of these two principal axes, composites developed with waste-derived fillers in which mechanical and tribological performance are pursued simultaneously deserve particular attention. Sources such as fish bone, shell flours, boron minerals and even ceramic powders recovered from end-of-life catalytic converters can be exploited in common matrices such as epoxy and polypropylene (Köse et al., 2025; Köse, 2024a; Ünal et al., 2023a). These studies clearly demonstrate that sustainability and engineering performance can reinforce rather than exclude one another.

The aim of this review is to evaluate, on the basis of the current literature, the mechanical and tribological performance of polymer-matrix composites developed with fillers—considering conventional and waste-derived additives together with current/advanced approaches—and to set out prospective research directions. Within this scope, polymer matrix materials, the classification of fillers, advanced filler systems, the matrix–filler interface, mechanical performance, tribological behaviour, solid-lubricated systems, adaptive composites, sustainable fillers and

green tribology, characterization, modelling and tribo-informatics, application areas, current trends, and prospective studies are addressed in turn.

Significance and Original Contribution of the Study

The significance of this review stems from its bringing together, within a single framework, two powerful yet frequently separately treated agendas of contemporary materials engineering—the pressure for sustainability and the requirement for high mechanical and tribological performance. In an era marked by circular-economy principles, resource scarcity and the burden of waste management, the valorization of agricultural, industrial and municipal wastes as fillers has become not merely an environmental necessity but also an engineering opportunity that is competitive in performance terms (Muthukutti et al., 2025; Soni et al., 2024).

A clear gap emerges when the existing review literature is examined: the majority of studies address either mechanical strength or friction-wear behaviour separately, and most remain confined to a single filler class (for example, only natural fibres, only PTFE reinforcements or only nanofillers) or to a single matrix family. Yet in real engineering components—such as sliding bearings, gears, bushings and seals—the load-bearing capacity of a material and its friction-wear response are demanded simultaneously and often in mutually conflicting ways. The original contribution of this review is that it (i) compares conventional mineral, ceramic, metallic and fibrous fillers together with waste- and bio-derived additives within a common performance framework, (ii) treats the mechanical and tribological criteria jointly as a trade-off and co-optimization problem, and (iii) bridges this classical axis with current approaches such as nanomaterials, self-healing systems, tribo-informatics and digital twins. In this way, the work aims to provide a synthesis that

unifies scattered findings around the dual-competence (mechanical and tribological) potential of sustainable fillers.

Polymer Matrix Materials

Polymer matrices can be examined in three main groups according to their curing and reprocessing behaviour. Thermoset matrices (epoxy, unsaturated polyester, vinyl ester, phenolic resins) offer high dimensional stability, thermal resistance and creep resistance owing to their cross-linked three-dimensional network structures; however, they are difficult to recycle because they cannot be re-melted and reshaped after curing. Epoxy resins, with their superior adhesion, low shrinkage and good mechanical properties, are the most frequently preferred thermoset matrix in filler-reinforced systems (Köse, 2024b; Köse et al., 2025; Rudawska et al., 2024).

Thermoplastic matrices (polyamide, polypropylene, POM, PTFE, cyclo-olefin copolymers) allow both mass production and recyclability because they can be reshaped in the melt. This group is also critical for tribological applications; the low friction coefficients and good wear resistance of semi-crystalline thermoplastics make them prominent as bearing and gear materials (Zhang et al., 2022; Ünal et al., 2025). Because moisture uptake by these matrices, particularly polyamides, can alter their mechanical and tribological properties, the service environment must be taken into account. Elastomeric matrices (EPDM, natural and synthetic rubbers) are used in applications requiring high flexibility, sealing and impact damping; in these matrices, filler and fibre reinforcement can substantially modify the rheological behaviour and mechanical strength (Halitoğulları et al., 2025).

Matrix selection is directly related to the targeted service temperature, chemical environment, load type and cost constraints.

Table 1 summarizes the typical properties and application areas of the principal matrix groups.

Table 1. Typical properties and application areas of polymer matrix groups

Matrix group	Representative polymers	Distinctive properties	Typical applications
Thermoset	Epoxy, polyester, vinyl ester	High stiffness and thermal stability; difficult to recycle	Structural panels, coatings, filled cast parts
Thermoplastic	PA, PP, POM, PTFE, COC	Reprocessable; good tribological behaviour	Bearings, bushings, gears, seals, automotive parts
Elastomer	EPDM, natural/synthetic rubber	High flexibility and sealing; damping	Seals, vibration isolators, hoses

Source: Compiled by the author on the basis of the current literature.

Classification of Fillers

Fillers can be classified in various ways according to their function and origin. A traditional distinction is drawn between reinforcing fillers, which impart strength to the material, and extender fillers, which mainly provide volume and cost advantages. A more useful classification for engineering purposes is based on the chemical nature and geometry of the filler.

Mineral and ceramic fillers (silica, calcium carbonate, boron compounds, boron nitride, alumina, hydroxyapatite) generally increase hardness, thermal stability and wear resistance; some boron compounds also act as flame retardants (Köse, 2024b; Rudawska et al., 2024). Boron-based particles have likewise been shown to yield favourable results in thermoplastic matrices from both mechanical and tribological standpoints (Gul et al., 2025). Metallic powder fillers (aluminium, copper) contribute to thermal and electrical conductivity while also providing mechanical stiffening at certain loadings (Köse, 2024c). Solid-lubricant fillers (graphite, MoS2,

PTFE powder) improve tribological performance by lowering the friction coefficient (Ünal et al., 2025; Zhang et al., 2022). Fibrous reinforcements (glass fibre, carbon fibre, natural fibres) provide large increases in tensile and flexural strength but introduce orientation-dependent anisotropic behaviour (Halitoğulları et al., 2025; Taj et al., 2025). Finally, bio- and waste-derived fillers (plant fibres, shell flours, fish-bone derivatives, waste PTFE and recovered ceramic powders) form a growing class aligned with sustainability objectives (Köse et al., 2025; Köse, 2024a; Muthukutti et al., 2025; Kamal et al., 2026).

Table 2 summarizes these principal filler classes together with representative examples and their typical effects on mechanical and tribological performance; the table should be read as indicating trends rather than absolute values.

Table 2. Principal filler classes in polymer composites and their typical effects

Filler class	Representative examples	Typical mechanical effect	Typical tribological effect
Mineral/ceramic	Silica, boron compounds, alumina, hydroxyapatite	Increased hardness and stiffness; reduced ductility	Higher wear resistance; loading-dependent friction
Metallic powder	Aluminium, copper	Moderate stiffening; increased thermal conductivity	Risk of abrasive wear at high loadings
Solid lubricant	Graphite, MoS2, PTFE powder	Limited effect on stiffness	Marked drop in friction; transfer film
Fibrous reinforcement	Glass fibre, carbon fibre, natural fibre	Large increase in tensile/flexural strength	Direction-dependent wear; fibre–matrix debonding

Nano/2D	Graphene, MXene, h-BN, nanocellulose	High stiffening at low loading	Marked reduction in friction and wear
Waste/bio-derived	Fish bone, shell flour, waste PTFE, recovered ceramic	Moderate improvement, depending on loading and surface treatment	Wear resistance close to conventional fillers at a suitable interface

Source: Compiled by the author on the basis of the current literature.

Advanced Filler Systems: Nanomaterials and Two-Dimensional Materials

One of the most notable developments in filler technology over the past decade has been the use of nanoscale and two-dimensional (2D) materials in polymer matrices. The distinguishing advantage of these materials is the exceptionally large interfacial area per unit mass and their superior intrinsic properties; as a result, appreciable mechanical stiffening and tribological improvement can be achieved even at very low loadings (often below 2 wt%). Graphene and its derivatives, owing to their high mechanical strength and the low shear resistance of their layered structure, act as both reinforcements and solid lubricants; the transfer method of graphene to the polymer surface and its interfacial adhesion directly determine the resulting friction and wear resistance (Yallew et al., 2023).

The MXene family of transition-metal carbides and nitrides (for example, $\text{Ti}_3\text{C}_2\text{Tx}$), with its rich surface chemistry, high conductivity and layered morphology, is a prominent filler class in polymer composites for both tribological and corrosion resistance; MXene reinforcement is reported to reduce wear by forming a protective tribofilm during sliding (Cai et al., 2022). Recent reviews of MXene tribology emphasize the potential of these materials for lubrication and wear resistance as well as open problems such as dispersion and stability (Stoll et al., 2025). Hexagonal boron nitride (h-BN), an electrically insulating solid lubricant that remains stable

even at high temperatures, offers a complementary option to graphene. The common challenge of these 2D materials is their tendency to agglomerate due to their high surface energies and the difficulty of achieving homogeneous dispersion and a strong interfacial bond; surface functionalization is therefore the decisive step for performance in these systems. The mechanical–tribological improvement offered by nano and 2D fillers has largely been demonstrated at the laboratory scale and within narrow loading windows, while agglomeration together with cost and scalability limitations remain significant obstacles.

Another nanomaterial class prominent along the sustainability axis is nanocellulose derived from plant sources. Cellulose nanocrystals (CNC), owing to their high specific strength, production from renewable sources and biodegradability, constitute an environmentally friendly alternative to conventional nanofillers (Veloso et al., 2023). Thus the agendas of nanotechnology and sustainability converge under the umbrella of bio-derived nanofillers.

The Matrix–Filler Interface and Surface Modification

The performance of a composite is determined less by the properties of its constituents than by the quality of the interface between them. Because the external load is transferred from the matrix to the filler through this interface, a strong and continuous interfacial bond is the precondition for realizing the reinforcing potential of the filler. At a weak interface, by contrast, filler particles readily debond from the matrix under load and become sites of void and crack initiation; in this case the filler ceases to be a reinforcement and can become a source of defects (Ge et al., 2026).

The incompatibility problem is pronounced when non-polar matrices (for example, polypropylene) are combined with polar or hydrophilic fillers. To overcome this problem, silane coupling

agents, compatibilizer copolymers (for example, maleic-anhydride-grafted polypropylene) and various surface treatments are used. These treatments render the filler surface compatible with the matrix, increasing wettability and strengthening the interfacial bond (Muthukutti et al., 2025). In waste-derived fillers, surface treatment is also critical for removing organic impurities and reducing moisture content.

In a study in which a fish-bone-derived additive was evaluated in an epoxy matrix, the particles obtained by modifying the bone were shown to disperse better within the matrix and to contribute positively to both mechanical and tribological performance (Köse et al., 2025). Similarly, the porous structure of mesoporous silicon dioxide improves interfacial load transfer by enhancing mechanical interlocking with the matrix (Köse, 2024b).

Simultaneous Optimization of Mechanical and Tribological Performance

A critical point frequently overlooked in the design of filler-reinforced polymer composites is that mechanical and tribological performance often do not improve in the same direction. As the loading of a hard mineral or ceramic filler is increased, the elastic modulus and hardness rise, but the same particles can reduce ductility and impact resistance and, at high loadings, can loosen and trigger three-body abrasion. Solid lubricants such as graphite, MoS₂ or PTFE, by contrast, markedly reduce the friction coefficient but contribute little to stiffness and may even weaken the load-bearing capacity. Consequently, the filler loading that maximizes mechanical strength and the loading that minimizes friction and wear do not coincide in most systems. For this reason, filler type, loading, particle size and surface treatment must be addressed not for a single performance metric but within a multi-objective optimization space in which the mechanical and tribological response are balanced

jointly. The central thesis advanced in this review is that the value of waste- and bio-derived fillers must likewise be assessed against this dual-competence criterion.

The effect of fillers on mechanical performance is explained essentially by three interrelated factors: the elastic and hardness properties of the filler itself, the homogeneity of its dispersion within the matrix, and the efficiency of stress transfer at the interface. Adding a hard filler generally raises the elastic modulus and hardness; however, if the interface is weak or agglomeration occurs, these particles become stress-concentration sites and can lower tensile strength and ductility. For this reason, an optimum behaviour is reported for most systems in which strength increases up to a certain critical filler loading and decreases thereafter (Köse, 2024b; Köse, 2024c). In the literature, this critical loading is typically concentrated in the range of about 5–15 wt% for micron-scale mineral and ceramic fillers, around 10–20 wt% (from a tribological standpoint) for solid lubricants, and at much lower values of about 0.5–2 wt% for nano and 2D fillers.

Particle size is decisive in this behaviour. Fine (submicron and nanoscale) fillers, by offering a far larger interfacial area per unit volume, can provide appreciable stiffening even at low loadings; however, they are prone to agglomeration owing to their high surface energies. Micromechanical models such as Halpin–Tsai and Mori–Tanaka are widely used to predict the variation of the elastic modulus with filler loading. These models predict only elastic/mechanical properties; they do not directly predict tribological behaviour and reflect the effects of agglomeration and interfacial slip only to a limited extent.

Studies conducted with mineral-based fillers clearly reveal these trends. In epoxy composites reinforced with mesoporous silicon dioxide, improvements in hardness and dimensional stability were observed up to a certain loading, whereas at high loadings the

stress-concentrating effect of the pores became dominant (Köse, 2024b). In boric-acid-filled polypropylene composites, the filler loading was found to be the principal variable governing mechanical performance (Ünal et al., 2023a); in epoxy/boric-acid systems, the main contribution of boric acid is reported to be flame retardancy (Rudawska et al., 2024). In metallic-powder fillers, in aluminium-powder-filled cyclo-olefin copolymer composites, the balance between the conductivity and hardness contribution of the powder and the ductility of the matrix required careful selection of the filler loading (Köse, 2024c). The effect is more pronounced in fibrous reinforcements: the addition of glass fibre to an EPDM matrix provided a notable increase in tensile and flexural strength, an increase found to depend on the quality of the fibre–matrix bond (Halitoğulları et al., 2025); in natural-fibre systems, filler additives have been shown to enhance mechanical performance in a complementary manner (Taj et al., 2025).

Tribological Behaviour: Fundamentals and Mechanisms

The tribological behaviour of polymer composites is governed by mechanisms of its own that are partly independent of the mechanical properties. Friction and wear are not material constants but system responses jointly determined by the material pair, the contact conditions and the environment. For this reason the same composite can behave very differently under different load, speed and counterface conditions (Ge et al., 2026; Panin et al., 2022). To give a numerical frame to these qualitative trends: while the friction coefficient for unfilled POM and polyamide is typically of the order of $\mu \approx 0.3\text{--}0.5$, with graphite or PTFE reinforcement it can fall to the $\mu \approx 0.10\text{--}0.20$ band, and in PTFE-based systems to the $\mu \approx 0.05\text{--}0.15$ level (Zhang et al., 2022; Deshwal et al., 2024). Similarly, the specific wear rate in engineering polymer composites is mostly reported in the range $10^{-6}\text{--}10^{-4}$ mm³/N·m, while in optimized PTFE/PEEK and nanofilled systems ultra-low wear

values of the order of $10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$ can be reached. Table 3 summarizes these typical magnitudes.

Table 3. Typical friction-coefficient and specific-wear-rate magnitudes by filler class

System / filler	Typical friction coefficient (μ)	Typical specific wear rate ($\text{mm}^3/\text{N}\cdot\text{m}$)
Unfilled POM/PA	$\approx 0.3\text{--}0.5$	$10^{-5}\text{--}10^{-4}$
Graphite- or PTFE-reinforced	$\approx 0.10\text{--}0.20$	$10^{-6}\text{--}10^{-5}$
PTFE-based (fibre/ceramic-reinforced)	$\approx 0.05\text{--}0.15$	$10^{-7}\text{--}10^{-5}$
Nano/2D-filled (optimized)	$\approx 0.08\text{--}0.20$	$10^{-7}\text{--}10^{-6}$

Source: Typical order-of-magnitude literature ranges compiled on the basis of Zhang et al. (2022), Deshwal et al. (2024) and Panin et al. (2022).

During sliding contact, material is transferred from the polymer surface to the counterface, and a layered transfer film forms over time. Not only the presence of this film but also its thickness, coverage of the counterface, adhesion strength and chemical composition are decisive. A thin, continuous, well-adhered and—in PTFE-based systems—fluorine-rich transfer film converts direct polymer–metal contact into polymer–polymer contact, thereby lowering both friction and wear rate; in high-performance composites, wear resistance is emphasized to be largely associated with the formation and stabilization of this film (Panin et al., 2022).

The principal wear modes in polymers are adhesive wear, abrasive wear, fatigue/delamination and corrosive-chemical wear. Which mechanism dominates is determined by a thermo-mechano-chemical coupling in which heat generation, mechanical deformation and chemical transformations at the interface interact (Ge et al., 2026). The loose wear debris (third body) released during sliding either reduces friction or, through three-body abrasion, accelerates wear, depending on particle size and hardness. The

relationship of wear rate to contact pressure and sliding distance is classically summarized by the Archard model; moreover, for many polymers, once the product of pressure and speed exceeds a certain limit value (the PV limit)—usually associated with the service temperature approaching the glass-transition temperature—an abrupt increase in wear is observed owing to thermal softening. In self-lubricating systems this PV limit is reported to rise markedly. Table 4 summarizes the principal wear mechanisms.

Table 4. Principal wear mechanisms in polymer composites

Mechanism	Dominant condition	Characteristic trace
Adhesive wear	Strong interfacial adhesion, low speed	Transfer film, smooth surface
Abrasive wear	Hard counterface or hard filler	Scratches, grooves, micro-cutting
Fatigue/delamination	Repeated loading, cyclic contact	Layered separation, flaking
Third-body wear	Loose wear debris	Rolling track or three-body scratching

Source: Adapted from Ge et al. (2026) and Panin et al. (2022).

The intrinsic and extrinsic factors governing tribological performance must not be overlooked either. While intrinsic properties such as the glass-transition temperature, crystallinity and cross-link density establish the baseline behaviour, temperature, moisture, counterface roughness and lubrication conditions often override them. In particular, there is an optimum range for counterface roughness (R_a): on very smooth surfaces the transfer film cannot adhere adequately, whereas on very rough surfaces abrasive wear becomes dominant. Moreover, the running-in stage and the maturation of the transfer layer show that the tribological response evolves over the material's service life; caution is therefore required in generalizing short-duration test results to long service conditions (Ge et al., 2026).

Solid Lubricants and Self-Lubricating Composites

In applications where lubricant cannot be supplied or where fluid lubrication is undesirable owing to contamination, self-lubricating polymer composites offer an important solution. In these systems, solid lubricants such as graphite, molybdenum disulphide (MoS₂) and PTFE powder reduce friction by forming a low-shear-resistance film on the counterface during sliding. The addition of graphite to a POM matrix markedly reduced the friction coefficient and wear rate compared with neat POM (Ünal et al., 2025). In POM composites filled with different types of PTFE, the lowest friction and wear were shown to be achieved with PTFE particles forming a smooth and continuous transfer film (Zhang et al., 2022); the addition of wax-based additives to a polyamide 6 matrix likewise reduced friction under bearing and gear conditions (Ünal et al., 2023b).

PTFE-based systems, owing to their low intrinsic friction coefficients, hold the position of reference materials; however, the high wear rate of neat PTFE makes filler reinforcement imperative. In PTFE composites reinforced with glass fibre, carbon fibre, bronze and ceramic particles, the wear rate is reported to be reduced by one to several orders of magnitude (Deshwal et al., 2024). A recent study in which waste PTFE was revalorized with high-strength carbide ceramics further shows that tribo-mechanical, thermal and electrical performance can be improved simultaneously (Kamal et al., 2026). In hybrid filler systems, when the load-bearing of a hard ceramic is combined with the low-shear-resistance film provided by a solid lubricant, the resulting synergy can exceed the sum of the individual contributions of the constituents; however, since antagonistic effects can also arise from agglomeration, the composition must be carefully optimized.

Adaptive and Self-Healing Composites

Traditional composite design focuses on preventing damage; self-healing composites, by contrast, offer an approach that departs from the traditional design philosophy through their ability to recover the damage that occurs, partly or fully. These systems can operate through intrinsic (reversible chemical bonds, thermally re-flowing matrices) or extrinsic (release of healing agents stored in microcapsules and microchannels onto the crack surface) mechanisms and can partially re-establish mechanical integrity under cyclic loading (Irzhak et al., 2022; Sharma et al., 2026). Because self-healing mechanisms have largely been developed for bulk damage repair, their adaptation to surfaces under sliding contact—wear being a surface phenomenon—remains a largely conceptual and early-stage field of research.

Another advanced direction is that of adaptive and multifunctional composites that respond to external stimuli (temperature, moisture, light). Four-dimensional (4D) printing, the time-related dimension of additive manufacturing, enables the production—through shape-memory polymers and stimulus-responsive fillers—of structures that can change their shape or function after printing (Mahmood et al., 2024). Combining these approaches with filler-reinforced tribological systems opens the way to stimulus-responsive surfaces that can adapt their friction and wear behaviour to operating conditions.

Sustainable and Waste-Derived Fillers and Green Tribology

As circular-economy principles gain increasing weight in materials science, the valorization of wastes as fillers has become a research field in its own right. This approach has a twofold benefit: it lowers the environmental footprint by reducing the use of virgin raw materials, and it creates a value-added use for wastes that would otherwise have to be disposed of (Muthukutti et al., 2025; Soni et al., 2024). Agricultural wastes (shells, rice husk, olive stone, bagasse

ash), industrial by-products and municipal green wastes are the most frequently studied sources. When appropriate pretreatment is applied, notable increases in stiffness and improvements in dimensional stability can be obtained in agro-waste-filled polypropylene composites (Zhiltsova et al., 2024).

A body of evidence that concretizes this perspective can be seen in the author’s series of studies spanning different matrices and waste sources. On the thermoset side, the modification of fish-processing-waste bones to improve both mechanical and tribological performance in an epoxy matrix (Köse et al., 2025), the valorization of nano-sized ceramic powders recovered from end-of-life catalytic converters in epoxy composites (Köse, 2024a), and the strengthening of interfacial interlocking by mesoporous silicon dioxide (Köse, 2024b); on the thermoplastic side, boric-acid-filled polypropylene (Ünal et al., 2023a), POM/graphite (Ünal et al., 2025), polyamide 6/wax (Ünal et al., 2023b) and aluminium-powder-reinforced cycloolefin copolymer (Köse, 2024c) systems; and on the elastomer side, glass-fibre-reinforced EPDM composites (Halitoğulları et al., 2025) provide mutually complementary findings. Although these studies appear as separate systems when considered individually, they point to a common pattern: (i) local and waste-derived additives can be technically evaluated across all three principal matrix families, (ii) performance improves up to a certain critical filler loading in each system and declines thereafter, and (iii) the decisive variable is frequently the quality of the matrix–filler interface rather than the filler itself. Table 5 summarizes this body of evidence.

Table 5. An integrated view of the author’s studies on composites with waste- and local-source fillers

System (matrix + filler)	Principal observed effect	Reference
Epoxy + modified fish bone	Improvement in mechanical and tribological performance	Köse et al., 2025

Epoxy + catalytic-converter ceramic	Filler function via waste valorization	Köse, 2024a
Epoxy + mesoporous silica	Interfacial interlocking and hardness increase	Köse, 2024b
PP + boric acid	Loading-governed; flame retardancy	Ünal et al., 2023a
POM + graphite	Reduction in friction and wear	Ünal et al., 2025
PA6 + wax	Reduced friction under bearing/gear conditions	Ünal et al., 2023b
COC + aluminium powder	Hardness/conductivity–ductility balance	Köse, 2024c
EPDM + glass fibre	Increase in tensile and flexural strength	Halitoğulları et al., 2025

Source: Compiled from the author's relevant publications.

These efforts acquire an integrated framework under the concept of green tribology. Bringing together environmentally friendly lubricants, biodegradable and waste-derived materials, energy efficiency and the reduction of friction-wear losses, green tribology is a sustainability-oriented philosophy of tribological design (Freschi et al., 2022). Within this framework, the joint consideration of technical performance with life-cycle assessment (LCA) is becoming increasingly widespread; studies in which mechanical performance and environmental impact are evaluated together in composites reinforced with natural fibres and end-of-life textiles are prominent (Arya et al., 2024). The principal environmental advantage of waste-derived fillers over primary fillers is the low embodied energy and associated greenhouse-gas emissions of their production; the conversion of recycled polymers into composites by additive manufacturing is likewise an extension of the same circular approach (Kyriakidis et al., 2024).

Characterization Methods

Reliable evaluation of the performance of filler-reinforced polymer composites requires a set of complementary characterization methods. Mechanical behaviour is quantified

through tensile, flexural and impact tests and hardness measurements, generally conducted according to ASTM/ISO standards. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are used for thermal stability and phase behaviour; scanning electron microscopy (SEM) for microstructure and fracture-surface examination; and Fourier-transform infrared spectroscopy (FTIR) for chemical interactions (Köse, 2024b; Halitoğulları et al., 2025).

In tribological characterization, the most common configurations are the pin-on-disk and block-on-ring arrangements; the friction coefficient and wear rate are measured under controlled load and sliding speed. Microscopic examination of the worn surfaces is critical in identifying the dominant wear mechanism (Ünal et al., 2025; Zhang et al., 2022). Standardization of the test conditions (load, speed, temperature, counterface roughness and atmosphere) is essential for comparability across different studies (Panin et al., 2022).

Modelling, Data-Driven Design and Tribo-informatics

In addition to experimental methods, numerical and statistical modelling occupies an increasing place in composite design. While micromechanical models (Halpin–Tsai, Mori–Tanaka) predict the variation of elastic properties with filler loading, the finite element method (FEM) is used to examine stress distribution and load-bearing capacity at the machine-element scale. Design of experiments (DoE) and response-surface methodology are effective in the simultaneous optimization of filler loading, particle size and processing parameters.

Recently, these tools have merged with artificial intelligence and machine learning to give rise to an interdisciplinary paradigm termed tribo-informatics. Tribo-informatics aims to predict complex, multivariable phenomena such as friction and wear and to accelerate

materials discovery by bringing together experimental, simulation and literature data and processing them with data-mining and learning algorithms (Yin et al., 2023). For example, the tribological properties of PTFE composites have been shown to be predictable with gradient-boosting regression models trained on experimental data, with load and speed emerging as the most influential variables (Yan et al., 2024); the prediction of wear rate by machine learning in glass-fibre-reinforced PTFE composites has likewise given successful results (Deshpande et al., 2024). Recent studies combining process signals such as acoustic emission with learning models open the way to online (real-time) monitoring of polymer-interface wear (Chen et al., 2025). The reliability of these approaches depends on high-quality, standardized data of sufficient volume; data scarcity and non-standard test conditions are the principal limiting factors.

Principal Application Areas

Filler-reinforced polymer composites have a very wide range of applications. In the field of machine elements, self-lubricating bearings, bushings, gears and sliding seals are replacing metallic parts in applications requiring low friction and high wear resistance (Ünal et al., 2023b; Ünal et al., 2025; Deshwal et al., 2024). In the automotive and transportation sector, glass- and natural-fibre-reinforced thermoplastics and elastomer seals are widely used with the aim of weight reduction (Halitoğulları et al., 2025; Zhiltsova et al., 2024).

Biomedical and prosthetic applications, particularly together with finite-element-assisted design, constitute another important area of use for polymer and composite materials; biocompatible ceramic fillers such as hydroxyapatite allow both mechanical and biological requirements to be met together. In the construction, packaging and electronics sectors, composites with waste- and bio-

derived fillers are increasingly preferred for their sustainability and cost advantages (Muthukutti et al., 2025; Kyriakidis et al., 2024); in the energy and environmental fields, the conversion of waste materials into high-value-added composites directly aligns with circular-economy objectives (Kamal et al., 2026).

Current Trends and Open Problems

The current literature points to several distinct directions in the field of filler-reinforced polymer composites. Sustainability and circular-economy principles have become a central criterion in filler selection, and waste- and bio-derived fillers have begun to be evaluated as a competitive option in performance terms as well (Muthukutti et al., 2025; Köse et al., 2025). Nano and 2D materials and hybrid filler systems, by offering high performance at low loadings, can mitigate the trade-off between mechanical strength and tribological performance—albeit at the laboratory scale and within narrow loading windows (Cai et al., 2022; Yallew et al., 2023; Stoll et al., 2025). Data-driven design and tribo-informatics, in turn, are accelerating materials discovery by integrating with experimental work (Yin et al., 2023; Yan et al., 2024).

Nevertheless, important problems await solution in the field. In waste-derived fillers, source variability and reproducibility are the most fundamental obstacles to adoption at the industrial scale. The agglomeration and safe processing of nanofillers and the long-term durability of the matrix–filler interface under moisture and temperature cycling have not yet been sufficiently elucidated. The fact that tribological data are largely obtained under laboratory conditions and over short durations creates uncertainty in generalizing to real service life; and the lack of standardization of test conditions makes the direct comparison of quantitative results difficult (Ge et al., 2026; Panin et al., 2022).

Prospective Studies and Future Research Directions

The findings presented in this review and the problems yet to be resolved indicate that the field of filler-reinforced polymer-matrix composites stands at a threshold of maturity. The principal issue before the field is to establish an integrated research agenda that, moving beyond individual material successes, brings together sustainability, data-driven design and multifunctionality within a single framework. Below, five principal directions are addressed, with the current bottleneck, the proposed concrete research action and the expected scientific, industrial and environmental impact emphasized separately for each.

Artificial-intelligence-assisted tribo-informatics and data-driven materials design. The current bottleneck is that friction and wear data are largely produced with widely differing test rigs, conditions and reporting formats; this fragmentation hinders the creation of high-quality, sufficiently large datasets to feed learning algorithms (Yin et al., 2023). The proposed concrete action is to establish open and shareable tribological data repositories by standardizing experimental, simulation and literature data with a common metadata schema, and to train, on these data, explainable hybrid models that go beyond purely statistical prediction and are constrained by physical mechanisms (Yan et al., 2024; Deshpande et al., 2024). The importance of this direction lies in moving materials discovery from the trial-and-error paradigm that dominates today towards a prediction-based design philosophy; a successful tribo-informatics infrastructure will both markedly reduce development time and experimental resource consumption and, by scientifically elucidating the multivariable relationships extending from filler type, loading and interface treatment to the ultimate tribological response, will qualitatively raise the predictive power of the field.

Digital twin and predictive maintenance. The current bottleneck is that the wear behaviour of polymer-composite tribological elements is a time-evolving, multifactorial and often

nonlinear process, so that short-duration laboratory-scale data cannot be reliably generalized to real service life. The proposed concrete action is to build high-fidelity digital twins of a bearing, bushing or gear that are fed with real-time sensor data on operating conditions, and to couple these twins bidirectionally with wear models at the material scale; the digital-twin approaches maturing for rotating machinery provide a suitable basis for this transition (Inturi et al., 2024; Chen et al., 2025). The importance of this direction becomes apparent in its uniting the material and system scales within a single predictive framework; the ability to forecast the remaining useful life in advance will both increase industrial reliability and maintenance cost-efficiency by reducing unplanned downtime and premature part replacement, and lower the environmental footprint through resource and energy savings by optimizing the use of the material over its lifetime.

Self-healing, adaptive and biomimetic tribological surfaces. The current bottleneck is that self-healing mechanisms have largely been developed for bulk damage repair; yet, wear being a surface phenomenon, their adaptation to surfaces under sliding contact remains at the conceptual stage (Irzhak et al., 2022; Sharma et al., 2026). The proposed concrete action is to design healing-agent release responsive to sliding conditions and surface damage, to produce structures that can adapt their friction behaviour to operating conditions through 4D printing and shape-memory polymers (Mahmood et al., 2024), and to combine these approaches with nature-inspired low-friction surface architectures (Sharma & Grewal, 2023). The importance of this direction is that it makes possible a transition from a passive philosophy that merely seeks to prevent damage to a dynamic material behaviour that responds effectively to damage; these adaptive surfaces, which extend service life and reduce maintenance needs, will increase reliability in safety-

critical applications and contribute to resource efficiency by lowering the frequency of material replacement.

Advanced integration of sustainable nanofillers and waste valorization. The current bottleneck is that bio-derived nanofillers and secondary (waste-derived) materials are studied separately; hybrid designs that would simultaneously provide high performance and low environmental impact in the same system, and their measurable environmental justification, remain limited. The proposed concrete action is to co-design renewable and biodegradable nanomaterials such as nanocellulose (Veloso et al., 2023) together with secondary sources such as waste PTFE and recovered ceramics (Kamal et al., 2026; Köse, 2024a) in hybrid filler systems with complementary functions in view, and to integrate these designs with life-cycle assessment (LCA) from the outset. The importance of this direction lies in its potential to concretely eliminate the trade-off frequently assumed between sustainability and engineering performance; the joint optimization of technical criteria with environmental-impact indicators will place circular-economy principles at the centre of materials design, thereby reducing dependence on virgin raw materials and grounding the high-value use of wastes on a basis fully consistent with green-tribology principles (Freschi et al., 2022; Arya et al., 2024; Muthukutti et al., 2025).

Standardization and scalability. The current bottleneck is that the source variability and reproducibility problems inherent to waste-derived fillers, together with the lack of standardization of test conditions, constitute the most fundamental obstacle to transferring laboratory successes to the industrial scale. The proposed concrete action is to develop common pretreatment and characterization protocols for waste-derived fillers, to make the quantitative reporting of source variability a norm, and to document long-term behaviour through accelerated ageing tests. The importance of this direction

lies in its advancing the scientific maturity and technological reliability of the field simultaneously; common protocols, by ensuring comparability across different studies, will both raise the quality of tribo-informatics data repositories and open the way to the confident adoption of sustainable-filler composites in industry.

These five directions are not independent but parts of a whole that reinforce one another. The principal promise of the field in the coming period lies in the convergence of sustainability, data-driven design and multifunctionality within a single framework: standardized and open data infrastructures will enable the predictable design of materials developed with waste- and bio-derived fillers; digital twins will relate these materials to real service conditions; and self-healing and adaptive surfaces will endow them with the ability to respond to changing conditions over time. When this convergence is realized, filler-reinforced polymer composites will become not merely high-performance engineering materials but at the same time environmentally responsible, data-governed and functionally adaptive material systems.

Conclusions and Recommendations

Polymer-matrix composites developed with fillers offer a comprehensive and high-potential material platform for engineering applications that regard mechanical strength and tribological performance together. As emphasized in this review, the ultimate behaviour of the composite is determined not by the filler type alone but jointly by the filler loading, particle size, geometry, matrix selection and, predominantly, the quality of the matrix–filler interface. Current approaches such as two-dimensional materials, self-healing systems, tribo-informatics and digital twins are moving the field from traditional materials development towards a multifunctional and data-oriented design philosophy.

The most important conclusion drawn by this review is that sustainability and engineering performance should now be regarded not as a trade-off but as a pair of objectives that can be designed jointly. The value of waste- and bio-derived fillers lies not only in reducing the environmental footprint but in their becoming able—through appropriate pretreatment, loading and interface optimization—to compete with conventional fillers in mechanical and tribological criteria simultaneously. Combining this dual-competence perspective with tools such as tribo-informatics and life-cycle assessment constitutes the most productive line for advancing both the scientific originality and the industrial reliability of the field.

The priorities for future work that would contribute most to the maturation of the field may be listed as follows:

- Developing explainable machine-learning and tribo-informatics models integrated with experimental data, and creating open datasets.
- Adapting digital-twin and predictive-maintenance approaches to polymer-composite tribological components.
- Designing self-healing, adaptive and biomimetic tribological surfaces.
- Combining sustainable nanofillers with waste-derived secondary materials in hybrid systems and co-designing them with life-cycle assessment.
- Establishing standardized pretreatment, characterization and accelerated-durability protocols for waste-derived fillers.

Along these lines, studies deepening in the axes of standardization, long-term durability and data-driven design will

advance both the engineering reliability and the environmental sustainability of filler-reinforced polymer composites together.

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CHAPTER 4

A VALIDATED DYNAMIC MODEL AND MPC-BASED VIBRATION SUPPRESSION FRAMEWORK FOR AN INTEGRATED MOTORCYCLE–RIDER SYSTEM

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Introduction

Unlike four-wheeled vehicles, motorcycles are widely preferred due to advantages such as maneuverability and the ability to adapt easily to heavy traffic conditions. However, vibrations caused by road surface irregularities and sudden road-induced inputs are transmitted to the rider with limited isolation. Such unwanted vibrations are transferred directly to the vehicle body and the rider through the tires and suspension systems (Ferhath & Kasi, 2024; Zhang et al., 2026). Consequently, this negatively affects ride comfort, road holding, and vehicle stability, as well as the rider, particularly during prolonged exposure (Rakheja et al., 2020; Rizuan

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& Abeykoon, 2026). Damping and controlling unwanted road-induced vibrations significantly enhance both riding safety and comfort (Krishna et al., 2024). While road-induced vibrations are a primary source of vibration in motorcycles, efforts are made to attenuate vertical vibrations via the wheel and suspension systems before they are transmitted directly to the rider (Doria et al., 2013). Given the complex nature of the human body's components, treating the rider merely as a rigid mass does not provide an adequate description (Keppler, 2014). Consequently, because the frequency-dependent responses of the body's components vary, their reaction to external vibrations differs (Lohar & Bhende, 2026; Rizuan & Abeykoon, 2026; Singh et al., 2024). Ultimately, vibrations resulting from road-induced excitations are transmitted from the motorcycle to the rider simultaneously. Therefore, relying solely on a simple vehicle model is insufficient for vibration reduction; instead, a comprehensive model integrating both the motorcycle and the rider must be developed. From a biomechanical perspective, the effects of vibration vary across human body components due to their differing mass, stiffness, and damping characteristics (Ferhath & Kasi, 2024; Rizuan & Abeykoon, 2026). Prolonged exposure to vibration can lead to fatigue, discomfort, and health issues that affect rider comfort (Doria et al., 2013; Keppler, 2014). Thus, evaluating the integrated motorcycle-rider system is a crucial step in characterizing vibration behavior (Zhang et al., 2026).

Springs and shock absorbers are employed to support suspension systems in vehicles, aiming to reduce and dampen road-induced vibrations (Li & Chen, 2025; Rodrigues Moreira Resende Da Silva et al., 2021; Tseng & Hrovat, 2015). However, due to their fixed mechanical properties, suspension systems cannot maintain stable performance across varying road conditions, vehicle speeds, and rider parameters. In this context, researchers working on vibration control in vehicles such as motorcycles have focused on

active vibration control applications that provide high performance in varying conditions by optimizing dynamic response, as opposed to passive elements (Chaurasiya et al., 2025; Zhang et al., 2026). Classical vibration control approaches, such as traditional Proportional-Integral-Derivative (PID) and Linear Quadratic Regulator (LQR) control methods, are widely preferred (Garziad & Saka, 2019; Shahid & Wei, 2019). These control systems provide effective vibration control under the chosen control parameters. However, control effectiveness may prove insufficient due to physical constraints within the system and changes in disturbing dynamic inputs affecting control inputs. Such control approaches, where dynamic variable parameters like actuator limitations, suspension constraints, and physical constraints are determined by the traditional feedback signal based on past and present system responses, negatively impact stable control performance (Shahid & Wei, 2019). Therefore, Model Predictive Control (MPC), which determines control performance from the system's future response, becomes an alternative for systems dependent on variable dynamic conditions. With MPC, an optimal control parameter is determined by solving a constrained optimization problem based on a mathematical model that predicts future vibration responses over a finite time horizon (Mayne, 2014; Shahid & Wei, 2019). The MPC offers an effective approach to vibration control for the motorcycle and rider, thanks to its predictive capabilities and ability to handle physical constraints. Furthermore, actuator limitations and system responses are directly incorporated into the optimization problem (Mayne, 2014).

Advanced control techniques that represent rider components as a single mass while focusing on the vehicle structure and suspension systems are widely preferred in such studies (Bova et al., 2020; Sequenzia et al., 2015). However, the biomechanical dynamics of body components are neglected in vibration control

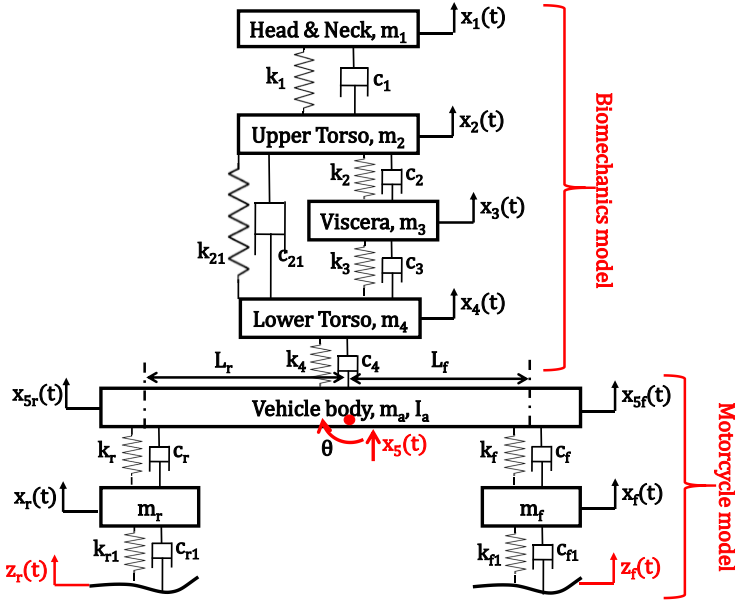
approaches(Sequenzia et al., 2015). In systems with multiple degrees of freedom, such as an integrated motorcycle-rider model, dynamic constraints directly affect both the predicted dynamic response and control performance(Barbagallo et al., 2016; Bova et al., 2020).

Considering physical and dynamic constraints, the motorcycle and rider model is represented by interconnected biomechanical dynamic properties corresponding to the basic body parts (Keppler, 2014). In this context, the main contribution of the study is the dynamic validation of the mathematical model using finite element modeling and the presentation of MPC-based vibration control aimed at reducing the dynamic response of both the driver and the motorcycle body through the validated model. Leveraging the predictive capability of MPC and considering physical constraints, parameters such as displacement, peak-to-peak values, and RMS levels are evaluated in both the time and frequency domains. Consequently, the study results account for changes in frequency-based dynamic characteristics alongside the reduction of vibration amplitude. In summary, the core contribution of this work lies in the integrated treatment of the motorcycle-rider model and MPC-based vibration.

Integrated Motorcycle–Rider Dynamic Model

Road-induced vibrations in motorcycles are transmitted to the rider through the suspension and tires. Unwanted vibrations not only affect driving comfort and safety but also, with prolonged exposure, can lead to biomechanical problems in the driver. The reduction and damping of vibrations transmitted to the rider depend on the dynamic behavior of the motorcycle's components (Keppler, 2014). In this context, rather than evaluating the motorcycle and the rider independently, the dynamic characteristics are analyzed using a motorcycle dynamic model that integrates the rider, as shown in Figure 1.

Figure 1 Schematic representation of the integrated dynamic model of the motorcycle and rider system



Kaynak: Yazar tarafından hazırlanmıştır.

Figure 1 illustrates the mathematical model of the dynamic behavior of the integrated motorcycle-rider system. In this context, a multi-degree-of-freedom mathematical model is considered that accounts for the combined interaction between the vertical movement of body parts in a biomechanical model representing the driver and the vertical and pitching motion of the motorcycle. In the schematic representation of the mathematical model, the motorcycle and the biomechanical model of the rider are designed as two distinct subsystems. While the vehicle body, tires, suspension, and wheels constitute the vehicle model, the driver's body regions, represented as the head, neck, upper torso, and lower torso, form the biomechanical structure.

As shown in the figure, four distinct masses are selected for the biomechanical model. The body segments of the rider are defined as follows: the head and neck region as m_1 , the upper torso as m_2 , the internal organs as m_3 , and the lower torso as m_4 ; the vertical motions of these body components are expressed by the variables x_1 , x_2 , x_3 , and x_4 , respectively.

In the biomechanical model, the mechanical interactions between components are modeled using spring-damper elements. The biomechanical connection separating the head region from the upper torso is represented by spring-damper elements (k_1 , c_1), while the dynamic interaction between the upper torso and the lower torso is expressed by k_{21} and c_{21} . Furthermore, the connection between the upper body and the internal organs is defined by spring-damper elements (k_2 , c_2), while the connection between the internal organs and the lower body is determined by k_3 and c_3 . Thus, rather than defining the dynamic behavior of the rider in the biomechanical model as a single lumped mass, it is modeled as a dynamic structure consisting of masses interconnected by mechanical elements. Mass, spring, and damping elements are also utilized in the integrated motorcycle-rider mathematical model to reflect the dynamic interactions between the components constituting the motorcycle model. The mass of the vehicle body, the moment of inertia, and the mass of wheels are represented by m_a , I_a , m_f , and m_r , respectively.

In the mathematical model, the vehicle's vertical motion is defined by the variable x_5 , while its pitching motion is described by the dynamic variable $\theta(t)$. Additionally, the vehicle's front and rear suspension parameters are defined by the spring-damper element pairs (k_f , c_f) and (k_r , c_r). In order to transmit road-induced vibration effects to the model, the interaction between the road and the wheels is represented by the dynamic elements (k_{f1} , c_{f1}) and (k_{r1} , c_{r1}). Here, the values of these parameters are determined by the tire stiffness and damping characteristics. Furthermore, in order to incorporate

irregularities arising from road surface undulations into the dynamic model, the effect on the front wheel is represented by the variable $z_f(t)$, while the effect on the rear wheel is transmitted via the road profile $z_r(t)$. When integrating road profiles, a speed-dependent time delay is applied, taking into account the distance between the front and rear wheels.

Consequently, the transmission of road input to the biomechanical model is not merely a problem based on external forces, but rather a dynamic problem that considers the kinematic and geometric parameters between the wheels. Spring-damper elements (k_4 , c_4) are used to couple the motorcycle and rider models within the schematic setup, thereby facilitating the transmission of road-induced vibrations from the motorcycle chassis to the rider. In this context, a bidirectional interaction is established through the transmission of rider-induced dynamic behavior to the vehicle body. Thus, the system is modeled to enable dynamic interaction between the rider and the vehicle.

1. Mathematical modeling

In order to develop a mathematical model of the biomechanical system comprising the motorcycle and the rider, the equations of motion must first be defined. In this context, the equations of motion for the dynamic model are derived using a multi-degree-of-freedom approach based on equivalent mass-spring-damper elements. When vertical and pitching motions are considered, the system is represented by a mathematical model with eight degrees of freedom $q = [x_1, x_2, x_3, x_4, x_5, \theta, x_f, x_r]$. The system's equations of motion have been derived using the Lagrange method and are formulated below as a set of eight independent equations.

$$m_1 \ddot{x}_1 + c_1 (\dot{x}_1 - \dot{x}_2) + k_1 (x_1 - x_2) = 0$$

$$\begin{aligned}
& m_2 \ddot{x}_2 + c_1(\dot{x}_2 - \dot{x}_1) + c_2(\dot{x}_2 - \dot{x}_3) + c_{21}(\dot{x}_2 - \dot{x}_4) + \dots \\
& \dots + k_1(x_2 - x_1) + k_2(x_2 - x_3) + k_{21}(x_2 - x_4) = 0 \\
& m_3 \ddot{x}_3 + c_2(\dot{x}_3 - \dot{x}_2) + c_3(\dot{x}_3 - \dot{x}_4) + k_2(x_3 - x_2) + k_3(x_3 - x_4) = 0 \\
& m_4 \ddot{x}_4 + c_{21}(\dot{x}_4 - \dot{x}_2) + c_3(\dot{x}_4 - \dot{x}_3) + c_4(\dot{x}_4 - \dot{x}_5) + \dots \\
& \dots + k_{21}(x_4 - x_2) + k_3(x_4 - x_3) + k_4(x_4 - x_5) = 0 \\
& m_a \ddot{x}_5 - c_4(\dot{x}_4 - \dot{x}_5) - c_f(\dot{x}_5 + L_f \dot{\theta} - \dot{x}_f) - c_r(\dot{x}_5 - L_r \dot{\theta} - \dot{x}_r) \dots \\
& -k_4(x_4 - x_5) - k_f(x_5 + L_f \theta - x_f) - k_r(x_5 - L_r \theta - x_r) = 0 \\
& I_a \ddot{\theta} - L_f \left[c_f(\dot{x}_5 + L_f \dot{\theta} - \dot{x}_f) + k_f(x_5 + L_f \theta - x_f) \right] - \dots \\
& \dots - L_r \left[c_r(\dot{x}_5 - L_r \dot{\theta} - \dot{x}_r) + k_r(x_5 - L_r \theta - x_r) \right] = 0 \\
& m_f \ddot{x}_f - c_f(\dot{x}_5 + L_f \dot{\theta} - \dot{x}_f) + c_{f1}(\dot{x}_f - \dot{z}_f) - \dots \\
& \dots - k_f(x_5 + L_f \theta - x_f) + k_{f1}(x_f - z_f) = 0 \\
& m_r \ddot{x}_r - c_r(\dot{x}_5 - L_r \dot{\theta} - \dot{x}_r) + c_{r1}(\dot{x}_r - \dot{z}_r) - \dots \\
& \dots - k_r(x_5 - L_r \theta - x_r) + k_{r1}(x_r - z_r) = 0
\end{aligned}$$

When formulating the mathematical model of the system, a dynamic model is established by making specific assumptions regarding the integration of the motorcycle and the rider. Initially, the motorcycle frame is considered rigid, and only the vertical and pitching movements of the motorcycle and wheels are taken into account. Furthermore, the body segments of the rider are represented by four distinct mass elements, with their dynamic interaction modeled using linear spring and damping elements. It is assumed that the angular changes during the motorcycle's pitching motion are small; consequently, the approximation $\sin(\theta) = \theta$ is used when deriving the equations of motion. The mass, damping, and stiffness matrices (M, C, K) are derived from the system's equations of motion. Using the system matrices, the state-space model is represented by the fundamental equation shown below.

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx + Du\end{aligned}$$

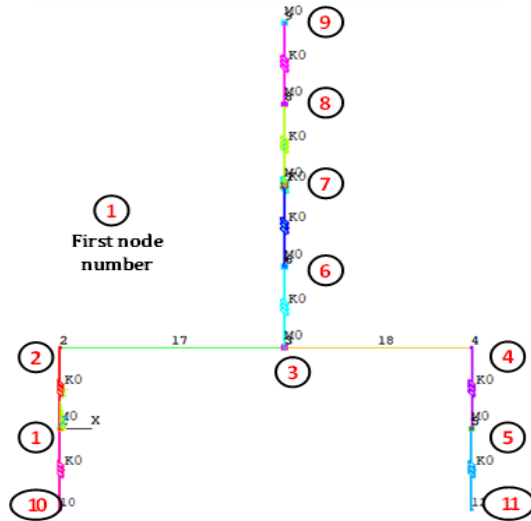
$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix}$$

Where, x is defined as the state vector and u as the input vector, while matrices A , B , C , and D are expressed as the system, input, output, and feedback matrices, respectively.

FE Analysis and Model Validation

A finite element (FE) model of the system is developed in ANSYS in order to validate the mathematical model of the integrated motorcycle-rider system and to analyze its dynamic characteristics. In order to compare the system's frequency results, a numerical FE model is constructed using mass, stiffness, and damping elements, as shown in Figure 2.

Figure 2 FE model in ANSYS



Kaynak: Yazar tarafından hazırlanmıştır.

Figure 2 shows that for each physical element of the system, rigid rod and spring-damping elements are preferred as equivalent node and connection elements in the FE model. In this context, the dynamic effects of physical parameters are incorporated into the FE model using a lumped-parameter approach. Consequently, the focus is placed on capturing vibration behavior and dynamic effects, rather than constructing a detailed 3D geometric model of the motorcycle and rider structure.

In the ANSYS model of the system, MASS21 elements are used to create mass components at specific nodes, thereby representing the dynamic characteristics of mass effects. COMBIN14 spring-damper elements are selected to facilitate dynamic interaction between the nodes. A massless rigid bar is defined using the MPC184 element to transmit vibration characteristics between the front and rear wheels via the motorcycle chassis. Node 3 is designated as the center of gravity of the vehicle, with the vehicle's mass and moment of inertia values integrated at this location. Rigid bars establish connections between the vehicle's front, rear, and center of gravity. The vehicle's wheel and suspension systems are similarly modeled using mass and spring-damper elements. Additionally, the biomechanical model is constructed using mass and spring-damper elements defined for various body segments. This enables the representation of relative motions between the motorcycle and the body segments of the rider within the FE model. Subsequently, a modal analysis is performed to validate the FE model against the mathematical model. While natural frequency results for the FE model are obtained via modal analysis, the frequency results for the mathematical model are calculated using the governing equation $(K - \omega^2 M)\phi = 0$. The modal analysis results for the integrated motorcycle-rider system are listed comparatively in Table 1 below.

Table 1 Natural frequencies of the integrated motorcycle-rider system

Order of natural frequency	Mathematical Model (MATLAB), [Hz]	FE Model (ANSYS), [Hz]
f_1	0.983	0.983
f_2	3.705	3.706
f_3	5.119	5.119
f_4	12.403	12.403
f_5	19.396	19.396
f_6	20.754	20.755
f_7	20.807	20.806
f_8	34.017	34.018

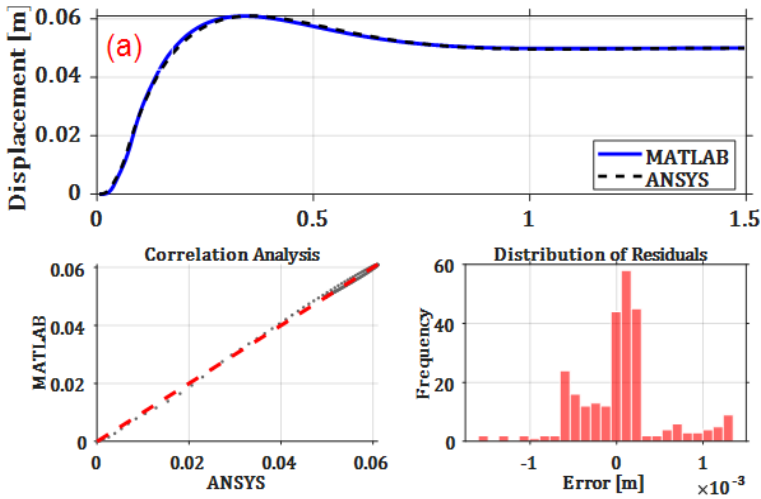
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Table 1 compares the mathematical model results with those of the FE model to validate the latter. An evaluation of the natural frequency results reveals that the absolute difference between the values is approximately 0.001 Hz, indicating good agreement between the mathematical and FE models. Specifically, the first, second, and third natural frequencies obtained from the FE model are 0.983 Hz, 3.706 Hz, and 5.119 Hz, respectively, while the corresponding values calculated by the mathematical model are 0.983 Hz, 3.705 Hz, and 5.119 Hz. While the first and third frequency values are identical for both models, a comparison of the second frequency values shows a deviation of approximately 0.027%.

As shown in Table 1, the other frequency results also demonstrate similar consistency between the two models. In this context, the modal characteristics of the mathematical model align accurately and reliably with those of the FE model, confirming that the FE model is represented consistently. The perfect fit of both

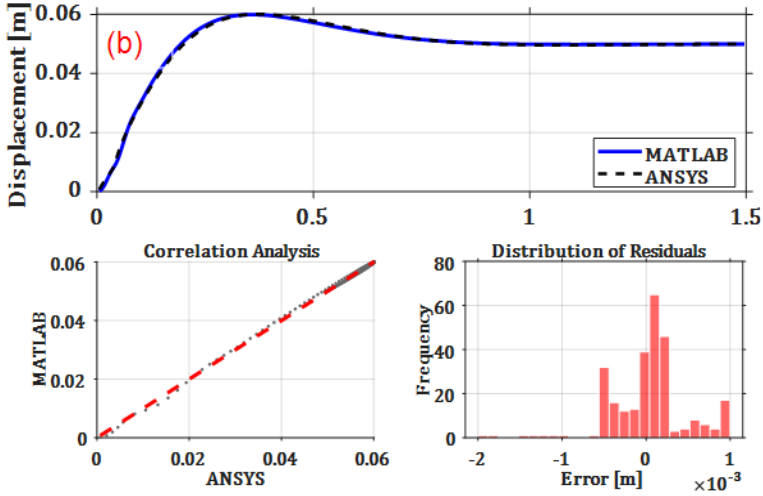
models and the accuracy of the mathematical model were evaluated in terms of modal characteristics, and the comparative vibration responses of the system's free vibration characteristic under step input are shown below. Furthermore, correlation analysis and residual distributions are calculated for the comparative vibration responses of displacements x_1 and x_5 , enabling a quantitative assessment of the models' agreement.

Figure 3 Transient response and statistical validation of the mathematical model against the FE model for x_1



Kaynak: Yazar tarafından hazırlanmıştır.

Figure 4 Transient response and statistical validation of the mathematical model against the FE model for x_5



Kaynak: Yazar tarafından hazırlanmıştır.

Figure 3 presents a comparative view of the x_1 displacement responses for the mathematical and FE models, while Figure 4 displays the x_5 displacement vibration results under a step input. An evaluation of the results reveals that the vibration responses of both models are consistent with each other throughout the entire time interval, accurately reflecting transient characteristics and damping behavior. Furthermore, a comparison of the correlation plots shows that the results from both the mathematical and FE models cluster along the $y=x$ line, indicating a linear correlation between the two models.

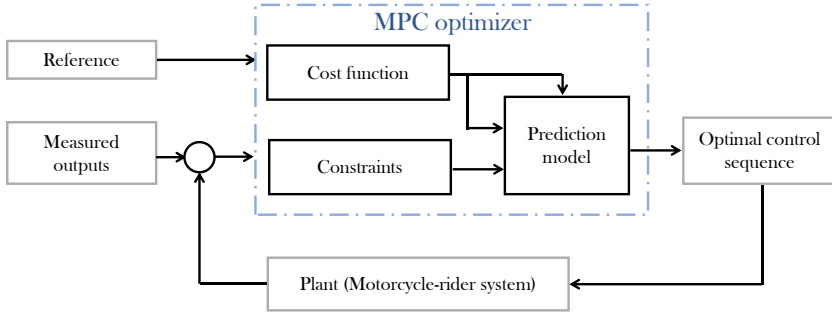
Additionally, since the error values in the histogram are in the order of approximately 10^{-3} m, it is observed that the discrepancy between the vibration results of the mathematical and FE models is at the millimeter level and that systematic deviations are minimal.

This indicates that the motorcycle components (mass, damping, and stiffness) used in the mathematical model are accurately represented in the FE model and that there is no dynamic mismatch between the models. The compatibility of the mathematical model with the FE models validates the proposed dynamic model approach in terms of modal characteristics and free vibration responses. This increases the reliability of the state-space approach for MPC-based vibration control analysis applied to the integrated motorcycle-rider system.

MPC-Based Controller Design

In this study, Model Predictive Control (MPC), which predicts vibration behavior and takes physical constraints into account, is preferred for vibration control of the integrated motorcycle driver multi-degree-of-freedom system. The MPC involves determining the optimal control action based on physical constraints by predicting the system's outcome at the next time step using a mathematical model. In short, it simulates the future vibration response using a numerical model based on the system's current data. The most critical aspect of the control system is defining a specific time interval and obtaining the optimal control response while accounting for physical constraints. In this section, the optimized control action is applied to the initial time interval, while optimal control parameters are recalculated using the prediction technique at the subsequent time step. The key feature distinguishing MPC from classical feedback control methods is its use of optimal control actions based on prediction and constraints. The block diagram for the MPC-based control strategy developed for the motorcycle-rider system is presented in the figure below.

Figure 5 MPC-based vibration control architecture for the motorcycle–rider system



Kaynak: Yazar tarafından hazırlanmıştır.

Figure 5 shows the closed-loop block diagram of the MPC-based vibration control design of the motorcycle and driver system mathematical model in the Matlab/Simulink environment. In the control application, the mathematical model is utilized as the controller's prediction model to derive the system's predictive dynamic behavior. Within the MPC framework, the system is expressed via a state-space model based on its mathematical model, incorporating the sampling period (T_s) of its continuous-time structure, as follows:

$$x_{k+1} = Ax_k + Bu_k + B_d d_k$$

Where, the variables $x(t)$, $u(t)$, and $d(t)$ are defined as the system state vector, the control input, and the external disturbance, respectively. Furthermore, the matrices A , B , and B_d represent the dynamic model of the system. Using this discrete-time model, a finite-horizon prediction is performed to control the system's dynamic behavior, and control performance is determined through a limited estimation mechanism. During the MPC prediction phase, the system response is estimated over a defined number of samples

using the mathematical model. At this stage, control performance is optimized by taking the system's physical constraints into account. For the motorcycle-rider system, the actuator capacity is selected as a physical constraint ranging from +1500 N to -1500 N. In the MPC-based control application, vibration control performance is determined based on a cost function. A general MPC objective function is formulated as shown below.

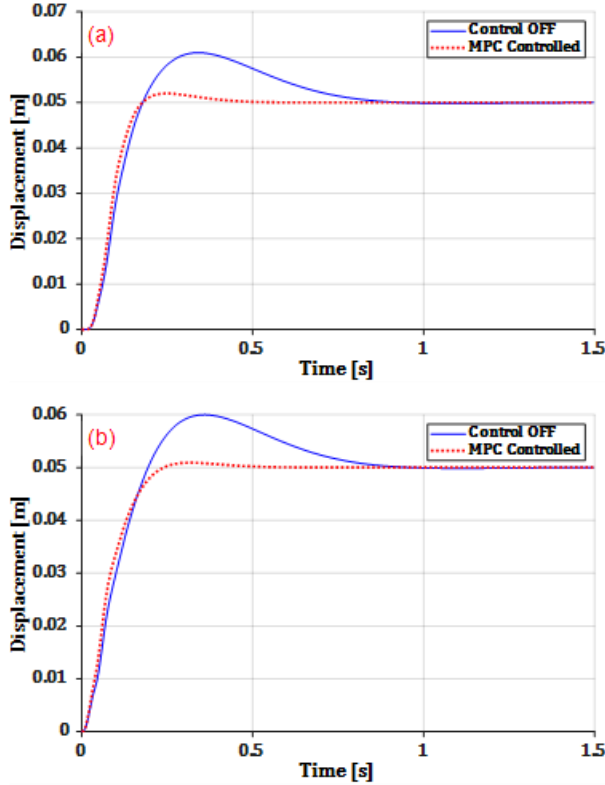
$$J = \sum_{i=1}^{N_p} \left[y_{k+i|k}^T Q y_{k+i|k} \right] + \sum_{i=0}^{N_c-1} \left[u_{k+i|k}^T R u_{k+i|k} \right] + \sum_{i=0}^{N_c-1} \left[\Delta y_{k+i|k}^T S \Delta u_{k+i|k} \right]$$

Where, the N_p and N_c parameters represent the prediction and control horizons, respectively. Q and R are the weighting matrices for vibration control and control effort, while S represents the control input rate of change. These parameters are selected by taking the magnitude of the system's vibration into account. Subsequently, the MPC-based vibration strategy incorporating predictive, optimizing, and physical constraints is simulated to perform vibration control for the integrated motorcycle and rider, and system responses are obtained.

Results and Discussion

In this section, the control performance of the integrated motorcycle-driver system under a 0.050 m step input yields vibration results in both the time and frequency domains using the designed MPC-based control approach. The vibration and frequency responses for both controlled and uncontrolled cases are illustrated in Figures 6 and 7.

Figure 6 Time-domain comparison of the uncontrolled and MPC-controlled responses for (a) x_1 , and (b) x_5



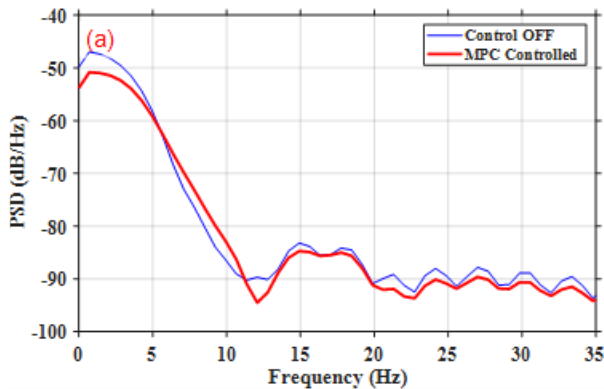
Kaynak: Yazar tarafından hazırlanmıştır.

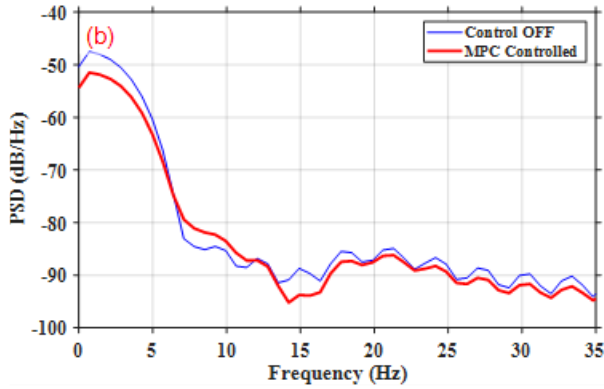
Figure 6 presents a comparison of the controlled and uncontrolled displacement responses for the motorcycle-rider system. Figure 6(a) shows the displacement results for x_1 , while Figure 6(b) displays the vibration results for x_5 , representing the vertical motion of the motorcycle. As seen in the figures, for the uncontrolled x_1 displacement signal, the vibration value is calculated to be approximately 0.062 m at the 0.35 s time step; for x_5 , this value is found to be approximately 0.060 m at the same time step. In the controlled case, the maximum vibration value is approximately

0.052 m, and the system tracks the steady-state value of 0.050 m. In this context, it can be stated that the overshoot during the transient phase of the system response is significantly reduced through the application of MPC.

As shown in Figure 6(a), for the integrated motorcycle-rider model subjected to a step input with an amplitude of 0.050 m, the maximum amplitudes of the controlled and uncontrolled x_1 vibration responses are found to be approximately 0.062 m and 0.052 m, respectively; it is observed that the system response is damped by approximately 84% with MPC. Figure 6(b) shows that the x_5 vibration responses are reduced by approximately 99%. While MPC significantly suppresses the peak values of the system response, it also ensures a smoother approach to the steady state. Furthermore, the steady-state values of the vibration responses converge to the step input amplitude of approximately 0.050 m; the MPC effect enables the system to reach its equilibrium position and, in particular, ensures the suppression of vibration amplitudes.

Figure 7 Effect of MPC-based control on the frequency-domain characteristics of (a) x_1 , and (b) x_5





Kaynak: Yazar tarafından hazırlanmıştır.

Figure 7 presents the uncontrolled vibration responses and the effectiveness of vibration control using MPC across the entire frequency range. As shown in Figure 7, it is observed that vibration amplitudes at all natural frequencies are reduced through the use of MPC. Furthermore, while significant vibration control effectiveness is evident in the 14–16 Hz frequency range, the control effect is less pronounced in the higher 20–35 Hz range. The results clearly demonstrate that the MPC approach not only reduces displacement amplitudes in the time domain but also effectively controls vibrations at natural frequencies. For a more effective assessment of the system's impact using the MPC approach, performance parameters of vibration responses are calculated and listed in Table 2 below.

Table 2 Performance parameters of a motorcycle for vibration control

	Control System	Overshoot (%)	Settling Time (s)	Peak-to-Peak	RMS
Displacement of head and neck, x_1	Control OFF	22.05	0.7755	0.0610	0.0119
	MPC	3.03	0.3410	0.0515	0.0106
Vertical displacement of the motorcycle, x_5	Control OFF	20.08	0.7865	0.0600	0.0107
	MPC	1.39	0.2200	0.0507	0.0095

Kaynak: Yazar tarafından hazırlanmıştır.

Table 2 summarizes the performance parameters of the integrated motorcycle-rider system used to evaluate the effectiveness of the proposed MPC. As shown in Table 2, the overshoot value for the displacement x_1 (representing the head and neck) drops from approximately 22.05% in the uncontrolled case to 3.03% with the MPC. The settling time of the vibration signal decreases from 0.775 s to 0.341 s, representing an improvement of approximately 56% due to the MPC. An improvement of approximately 16% is achieved in the peak displacement response, while a reduction of approximately 11% is observed in the RMS values. Furthermore, reductions of approximately 86% and 93% are observed in the overshoot values of the displacement vibration amplitudes for x_1 and x_5 , respectively. While reductions in maximum vibration amplitudes and RMS values are generally relatively limited, ranging from approximately 10-16%, MPC achieves a significant reduction in vibration amplitudes.

Overall, the results indicate that the proposed MPC effectively reduces system response amplitudes in both the time and frequency domains. The reduction in peak displacement and PSD

values of the vibration responses across the frequency range confirms the effective role of MPC in vibration control.

Conclusions

This study evaluates the vibration analysis and control of a dynamic model obtained by integrating the driver's biomechanical model into the motorcycle, using an MPC-based application. The integrated multi-degree-of-freedom dynamic model of the motorcycle and rider is formulated by accounting for fundamental vibration transmission mechanisms. The mathematical model is first validated against an equivalent finite element model developed in ANSYS. Model consistency is assessed through a comparison of frequency results and free vibration responses. In this context, it is observed that the mathematical and numerical models accurately represent the dynamic behavior under step input conditions. Subsequently, a mathematical model-based MPC (Model Predictive Control) strategy is implemented to control the vibrations of the integrated rider-motorcycle system. Therefore, MPC enables the prediction of the system's dynamic response and establishes an optimal control framework that accounts for physical constraints.

An analysis of the numerical results reveals significant improvements in the vibration amplitudes for both the rider and the motorcycle. It is evident that the system's vibration amplitudes decrease in the frequency domain across both low and high-frequency ranges. Furthermore, the proposed MPC-based vibration control is shown to not only suppress vibrations in the time domain but also yield significant improvements across the frequency spectrum. The results demonstrate that MPC is effective in suppressing vibrations, reducing overshoot, and shortening settling times, while providing a systematic framework for damping vibration responses. The experimental implementation of the

proposed MPC control approach in future work represents a significant next step toward practical application.

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