

Phase Transformation Behavior in the Preparation of High-Temperature Ceramic Materials and Its Influence on Mechanical Properties

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ABSTRACT Phase transformation behavior plays a critical role in determining the microstructural stability and mechanical reliability of high-temperature ceramic materials used in extreme-service environments. This study investigates the mechanisms governing phase evolution during ceramic preparation and analyzes their influence on strength, toughness, and structural integrity. Particular attention is given to the coupling among transformation kinetics, thermal history, lattice distortion, and residual stress development. Three key challenges are identified, including unstable phase-transition control, transformation-induced volumetric stress, and mismatches between phase-transition temperatures and processing parameters. To address these issues, a systematic optimization framework is proposed based on precise sintering regulation, additive-assisted phase stabilization, and multi-parameter collaborative control. The framework integrates thermodynamic analysis, phase-field simulation, finite-element modeling, and online process monitoring to establish quantitative relationships among processing conditions, phase evolution, microstructure formation, and mechanical performance. Furthermore, advanced processing approaches, including microwave-assisted sintering and intelligent parameter optimization, are incorporated to improve phase stability and suppress defect formation. The proposed methodology provides an engineering-oriented strategy for phase-transition regulation, microstructure control, and reliability enhancement of high-temperature ceramic systems, with potential applications in electromagnetic-assisted materials processing and advanced energy-related environments.

INDEX TERMS phase transformation, microwave-assisted sintering, microstructure regulation, high-temperature ceramics

I. INTRODUCTION

HIGH-TEMPERATURE ceramic materials, processed into specialized ceramic fibers and woven into heat-resistant structures, play an irreplaceable role in extreme environments such as aerospace engine components and high-temperature furnace linings due to their superior chemical stability and mechanical strength. This integration of ceramic properties with advanced weaving technology ensures the structural integrity and thermal insulation of critical components under severe operational stress. The quality of phase transformation behavior during the preparation process determines the microstructure and macroscopic mechanical properties. The phase transformation process is accompanied by a series of complex processes, including atomic rearrangement, lattice distortion, and stress accumulation, which can lead to reduced material density, uneven grain size distribution, and decreased strength and

toughness. However, the complexity of phase transformation makes precise control difficult, and uncontrolled phase transformation can easily cause performance fluctuations or failure.

II. SIGNIFICANCE OF STUDYING THE PHASE TRANSFORMATION BEHAVIOR OF HIGH-TEMPERATURE CERAMIC MATERIALS

A. THEORETICAL BASIS FOR IMPROVING THE MECHANICAL PROPERTIES OF HIGH-TEMPERATURE CERAMIC MATERIALS

Quantifying phase transformation behavior establishes the mechanistic framework for optimizing mechanical performance. Sintering-induced transformations dictate phase stability and grain boundary morphology, which exhibit a strictly coupled relationship with macroscopic mechanical properties [1]. Through systematic study of phase transfor-

mation kinetics and interface characteristics, the formation mechanisms of macroscopic properties—such as Vickers hardness (HV), flexural strength (σ_f), and fracture toughness (K_{IC})—can be quantified. Specifically, characterizing the volume fraction of the transformed phase (V_f) allows for the prediction of the transformation toughening contribution (ΔK_T), providing a mathematical basis for designing high-performance ceramic materials [2].

B. PROMOTING THE DEVELOPMENT OF ADVANCED CERAMIC MATERIAL PREPARATION TECHNOLOGY

The study of phase transition behavior can promote the innovation of ceramic material preparation technology. Through in-depth exploration of the thermodynamics and kinetics of phase transition, a quantitative relationship model between the phase transition process and process parameters can be established, providing support for the scientific planning of preparation process, significantly reducing the research and development delay, and improving the controllability of preparation [3]. At the same time, it can accelerate the development of advanced processes such as rapid sintering, microwave sintering, and spark plasma sintering, opening up new avenues for the preparation technology of high-temperature ceramic materials [4].

C. EXPANDING THE ENGINEERING APPLICATION FIELDS OF HIGH-TEMPERATURE CERAMIC MATERIALS

The three aspects of phase transition behavior research are interconnected and progressively deepen each other, forming the foundation for the development theory and application of high-temperature ceramic materials. The internal logical relationship is shown in Figure 1. Research on phase transition behavior will greatly expand the application range and performance boundaries of high-temperature ceramic materials. By precisely controlling the phase transition process, certain properties of materials can be improved in a targeted manner to meet the requirements of different working environments such as the thermal shock resistance of aero-engine blades and the radiation damage resistance of nuclear reactor components [5]. Research on phase transition behavior enables the development of multifunctional composite ceramic materials that can be seamlessly integrated into high-performance fiber structures, realizing a fusion of mechanical strength and thermal protection. This integration of structure and function promotes technological progress across the advanced materials industries by enhancing the durability of woven ceramic components [6].

III. PROBLEMS IN THE PREPARATION OF HIGH-TEMPERATURE CERAMIC MATERIALS

A. THE DIFFICULTY IN CONTROLLING THE PHASE TRANSITION PROCESS LEADS TO UNSTABLE PERFORMANCE

The phase transformation behavior during the preparation of high-temperature ceramic materials is affected by a

combination of factors such as temperature field distribution, atmosphere, and heating rate. These factors are interdependent, yielding non-linear transformation kinetics. The reaction is governed by athermal or isothermal kinetic pathways, making the phase evolution highly susceptible to thermal history. Minimal thermal fluctuations can deviate the transformation trajectory, leading to metastable phase retention. In addition, specific systems such as Zirconia-based ceramics (ZrO_2) and Alumina-Silica (Al_2O_3 - SiO_2) refractories exhibit multiple metastable phases. In Zirconia, for instance, the martensitic transformation from tetragonal to monoclinic phases involves a rapid, diffusionless rearrangement that is highly sensitive to critical cooling rates. Within a certain temperature range, several phase states can coexist or transform into each other, such as the order-disorder transitions found in Titanium Aluminides (TiAl). Such complex phase equilibrium relationships, governed by distinct thermodynamic drivers—shear-induced for martensite versus diffusion-controlled for order-disorder phases—bring significant difficulties to phase transformation control [7]. The uncertainty of phase transformation process control directly causes poor consistency of performance between batches of materials. The mechanical properties of materials prepared under the same process conditions fluctuate greatly, which seriously affects the reliability of materials and the feasibility of engineering applications [8].

B. VOLUME CHANGES CAUSED BY PHASE TRANSFORMATION LED TO MATERIAL CRACKING

During the phase transition, the crystal structure is re-organized. In Zirconia (ZrO_2), the t→m (tetragonal to monoclinic) transformation is accompanied by a volume expansion of approximately 3–5%, which is a primary cause of catastrophic failure. Conversely, in Silicon-based ceramics like Si_3N_4 during $\alpha \rightarrow \beta$ transformation, density changes are driven by dissolution-precipitation mechanisms. When the material changes from a low-density phase to a high-density phase, the volume will shrink, and conversely, the volume will expand. These system-specific volumetric effects inevitably cause internal stress gradients. Given the intrinsic low fracture toughness of ceramics, transformation-induced residual stresses exceeding the local cohesive strength trigger crack nucleation. These micro-defects coalesce and propagate during thermal cycling, resulting in macroscopic cleavage and structural failure. During the phase transition temperature window, asynchronous transformation kinetics between the surface and core generate significant internal stress gradients ($\nabla\sigma$). These gradients are driven by the transformation strain (ϵ_T), where the local residual stress (σ_r) can be estimated by $\sigma_r \approx \frac{E}{1-\nu} \Delta\epsilon_T$ (where E is Young's modulus and ν is Poisson's ratio). These high-magnitude stress concentration zones near the phase interface act as preferred initiation sites for cracks when the local stress intensity factor (K) exceeds the material's intrinsic fracture toughness (K_{IC}) [9]. For large-sized or complex-shaped ceramic parts, the

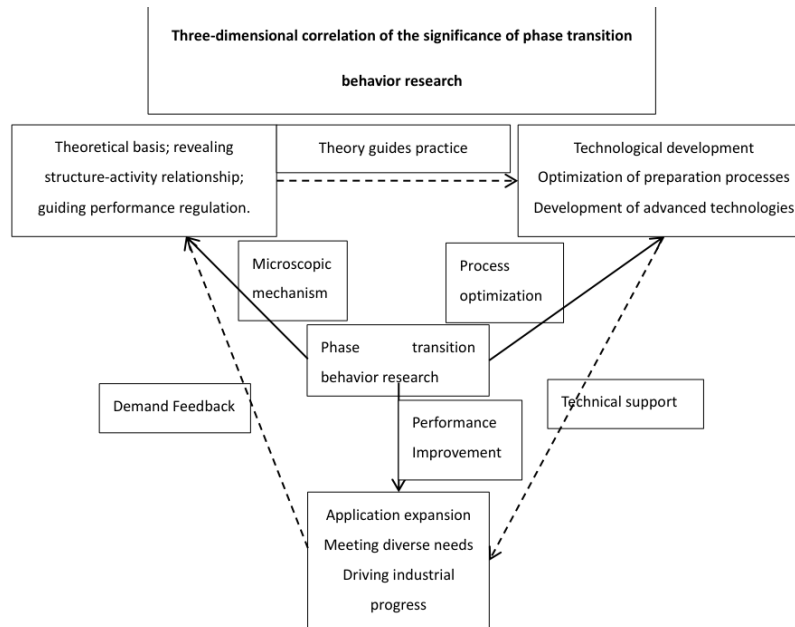


FIGURE 1. Three-dimensional correlation diagram of the significance of studying phase transformation behavior of high-temperature ceramic materials

cracking problem caused by the phase transition volume effect is more serious, which greatly affects the forming size and geometric complexity of the material and limits the application of high-temperature ceramic materials in large structural parts [10].

C. POOR MATCHING BETWEEN PHASE TRANSITION TEMPERATURE AND PREPARATION PROCESS PARAMETERS

The three problems that exist in the preparation process are interconnected and influence each other, forming a complete causal chain from microscopic phase transition runaway to macroscopic performance degradation, as shown in Figure 2. While the equilibrium phase transition temperature is an intrinsic thermodynamic property defined by the minimization of Gibbs free energy, the effective transformation temperature in practice is heavily modulated by nucleation barriers and growth kinetics. Dopant segregation at grain boundaries or solute clustering can locally shift the chemical potential, causing the effective transformation temperature (T_0) to deviate significantly from the bulk theoretical value. Consequently, achieving a complete match between sintering parameters and the phase transition temperature is difficult. In systems with a narrow transformation window, even high-precision sintering equipment may fail to provide "precise control" because the localized T_0 fluctuations trigger asynchronous phase evolution throughout the microstructure. When the sintering temperature setting value deviates from the optimal phase transition temperature, it may lead to incomplete phase transition or excessive phase transition. The former will cause a large amount of untransformed original phase to remain in the material, and the latter may trigger secondary phase transition or phase decomposition.

Both of these situations will deteriorate the microstructure and mechanical properties of the material. If the process parameters such as holding time and cooling rate are not coordinated with the phase transition kinetic characteristics, they will also affect the sufficiency of phase transition and the stability of the final phase [11]. The mismatch between process parameters and the localized phase transition requirements—exacerbated by dopant-induced T_0 shifts—results in secondary defects. These include abnormal grain growth in regions where the phase transition occurred prematurely and residual pores due to uncoordinated volumetric changes. Furthermore, solute depletion zones near grain boundaries may trigger the precipitation of brittle secondary phases. These microscopic defects aggregate to reduce the overall mechanical reliability of the high-temperature ceramic component [12].

IV. STRATEGIES FOR OPTIMIZING PHASE TRANSFORMATION BEHAVIOR OF HIGH-TEMPERATURE CERAMIC MATERIALS

A. PRECISE CONTROL OF SINTERING PROCESS TO OPTIMIZE PHASE TRANSFORMATION

Precise control of sintering parameters serves to manipulate both the thermodynamic driving force and the kinetic transformation rate. To achieve precise regulation, process parameters must be tailored to the specific transformation mechanism: Thermodynamic Regulation: Utilizing isothermal holds at the phase transition critical region to allow the system to minimize total Gibbs free energy, ensuring the equilibrium phase is fully realized. Kinetic Regulation: Controlling the cooling rate to either bypass or trigger diffusionless (martensitic) transitions, thereby preventing the kinetic stabilization of deleterious high-temperature phases

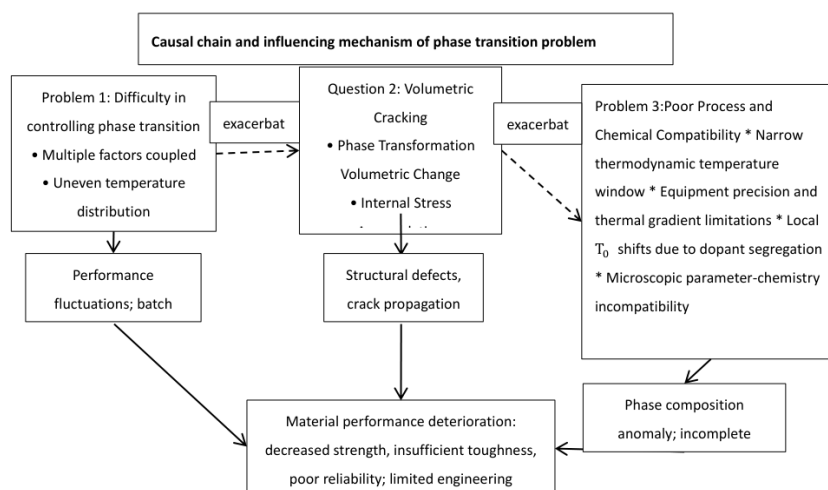


FIGURE 2. Causal chain and influencing mechanism of phase transformation problems in the preparation of high-temperature ceramic materials

at room temperature. First, an accurate correspondence between phase transformation temperature and sintering temperature should be established. Differential thermal analysis (DTA) and thermogravimetric analysis (TGA) should be used to accurately determine the characteristic phase transformation temperature of the material system. Based on this, a reasonable sintering temperature regime should be designed. To achieve precise control of the phase transformation process, different process parameters should be adopted for different phase transformation stages. Specific optimization schemes are shown in Table 1.

TABLE 1. Optimization Scheme for Sintering Process Parameters of Phase Transformation Process in High-Temperature Ceramic Materials

Phase Transition Stage	Temperature Control Strategy	Atmosphere Conditions	Main Function
Preheating stage	medium-speed heating	Inert atmosphere	Eliminate adsorbed gases and reduce thermal stress
Phase transition critical region	Slow heating	Based on system selection	Ensure the phase transition proceeds fully
High-temperature insulation section	constant temperature control	Vacuum or protective atmosphere	Stable target phase structure
Cooling stage	Program cooling	Inert atmosphere	Preventing high-temperature phase decomposition

The phase transition temperature range is approached by a segmented heating method. The heating rate is reduced when the temperature range is close to the phase transition temperature range, and the holding time of the temperature range is extended to ensure that the phase transition reaction is fully carried out and to avoid phase transition lag or incomplete transformation caused by excessive heating. For systems with multiple phase transition processes, a temperature platform should be set for each phase transition stage to ensure that each phase transition process proceeds smoothly. The cooling stage should not be

ignored. Controlling the appropriate cooling rate can prevent the decomposition of the high-temperature phase or the precipitation of the new phase and ensure the stability of the already formed phase structure [13]. In addition, improving the sintering atmosphere and using vacuum, reducing or oxidizing atmosphere can modulate the chemical potential gradients to alter the thermodynamic driving force while simultaneously adjusting the activation energy barriers of the kinetic process. This dual regulation promotes the formation of the target phase and inhibits the kinetic stabilization of deleterious metastable phases, and achieve precise control of the microstructure of the material at the phase transition level, so as to obtain high-temperature ceramic materials with uniform structure and excellent performance [14].

B. ADDITIVE AND COMPONENT DESIGN TO SUPPRESS HARMFUL PHASE TRANSFORMATION STRESS

Harmful stresses caused by phase transformation can be effectively suppressed through reasonable additive selection and component design. Appropriate amounts of sintering aids are introduced. To address the issue of phase transformation stress, suitable additive types are selected based on the characteristics of the material system. The introduction of additives addresses phase transformation stress through two distinct mechanical routes: 1. Thermodynamic Stabilization: Stabilizers (e.g., Y_2O_3) expand the thermodynamic stability field of desired phases (like tetragonal ZrO_2), reducing the chemical driving force for abrupt, large-volume transitions. 2. Kinetic Modification: Solid solution elements alter lattice parameters and diffusion coefficients, thereby increasing the activation energy barrier for harmful phase growth, effectively "smearing" the transformation over a broader temperature range to reduce stress gradients. The mechanisms of action and applicable conditions of various additives are shown in Table 2.

TABLE 2. Inhibition Mechanism and Effect of Different Types of Additives on Phase Transformation Stress

Additive types	Mechanism of action	Typical Representative	Main effects
Sintering aids	Lowering the phase transition temperature reduces the temperature gradient.	MgO, CaO	Reduce thermal stress
stabilizer	Stabilize specific crystal forms and avoid abrupt phase transitions.	Y ₂ O ₃ , CeO ₂	Suppressing volume effect
toughening phase	Crack deflection and bridging	SiC whiskers, ZrO ₂ particles	Improve fracture toughness
Solid solution elements	Adjusting lattice parameters to smooth phase transition	Al and Mg ions	To make phase transitions gradually evolve

The sintering temperature of the material can be reduced, so that the phase transformation can be carried out at a lower temperature, reduce the temperature gradient during the phase transformation process, and reduce the thermal stress level. Some additives can also participate in the phase transformation reaction, change the phase transformation path or stabilize a specific crystal form, and avoid large volume changes caused by phase transformation. By adopting the solid solution design strategy, an appropriate number of elements are added to the matrix to form a solid solution, which can adjust the lattice parameters and phase transformation temperature, make the phase transformation process more gradual, and reduce the violent volume effect caused by abrupt phase transformation. Incorporating secondary toughening phases or fiber reinforcements significantly enhances the critical stress intensity of the matrix. These reinforcements introduce energy dissipation mechanisms—such as crack deflection and bridging—that increase the total fracture energy (G_{IC}). For example, the addition of SiC whiskers can provide a bridging stress (σ_b) that counteracts the transformation-induced tensile stress, effectively shielding the crack tip and preventing catastrophic propagation. In addition, by using the composition gradient design to form a gradual phase composition distribution inside the material, the concentration of phase transformation stress can be dispersed to avoid excessive local stress. This material design method can also compensate for the change in phase transformation volume to a certain extent. In the phase transformation shrinkage zone, a component that causes volume expansion is added to achieve the purpose of internal stress balance, thereby fundamentally solving the cracking problem caused by phase transformation stress and improving the integrity and reliability of the material [15].

C. ESTABLISHING A PHASE TRANSITION-PERFORMANCE REGULATION SYSTEM THROUGH MULTI-PARAMETER COLLABORATIVE OPTIMIZATION

Establishing a multi-parameter synergistic optimization phase transformation-performance control system is a systematic solution to achieve breakthroughs in the performance of high-temperature ceramic materials. Optimizing a single parameter is rarely sufficient to simultaneously meet the requirements of phase transformation behavior and mechanical properties; therefore, it is necessary to consider the synergistic effects of parameters throughout the entire process, including raw material characteristics, powder preparation, forming process, sintering regime, and post-treatment. Establishing a systematic synergistic optimization system combines various technical means to form a closed-loop regulation structure where theoretical prediction and real-time control complement each other. The complete technical route is shown in Table 3.

TABLE 3. Phase Change-Performance Regulation Technology System Based on Multi-Parameter Coordination

Optimize the hierarchy	Technical means	Key Output	Application Purpose
Theoretical prediction	Phase field simulation, finite element analysis	Phase transformation path and stress distribution	Guiding process design
Experimental optimization	Orthogonal design, response surface methodology	Parameter-performance mathematical model	Determine the optimal parameter combination
Process monitoring	Online temperature/size detection	Real-time phase transition state data	Dynamically adjust process parameters
Intelligent optimization	Materials genome engineering, machine learning	Ingredient-Process-Performance Database	Accelerate the development of new materials

This study employs experimental design methods such as orthogonal experimental design and response surface methodology to investigate the influence of various process parameters on phase transformation behavior and material properties. A multivariate mathematical model is established to identify the optimal parameter combination among parameters, phase transformation, and properties. Numerical simulation techniques, including phase-field simulation and finite element analysis, are used to predict the phase transformation process and stress distribution under different parameter conditions, providing a theoretical basis for process optimization and reducing the randomness of experiments. An online monitoring system for phase transformation behavior is established to collect parameters such as temperature, atmosphere, and dimensions during sintering in real time. Feedback control is used to adjust process parameters, achieving intelligent and precise control of the phase transformation process. The concept of materials genome engineering is applied to the development of high-temperature ceramics, creating a database of composition, process, microstructure, and properties. Machine learning

algorithms are used to uncover hidden patterns, accelerating the design and optimization of new materials. Through this multi-scale, multi-method collaborative improvement strategy, the challenges of phase transformation control can be systematically overcome, establishing a complete technical system from microscopic phase transformation mechanisms to macroscopic performance regulation, promoting the development of high-temperature ceramic materials towards high performance and high reliability.

V. CONCLUSION

Phase transformation behavior during the preparation of high-temperature ceramic fibers is a key factor determining the mechanical properties of woven ceramic reinforcements. In-depth research into these phase transformation mechanisms and an accurate understanding of their laws are of great significance for developing high-performance ceramic fabrics capable of maintaining structural integrity under extreme thermal conditions. Currently, problems such as difficulty in controlling phase transformation, large volume effects, and poor process matching during preparation seriously affect the stable performance and engineering applications of materials. Through precise control of sintering processes, rational design of additives and components, and the establishment of multi-parameter synergistic optimization systems, it is possible to regulate the phase transformation process, suppress harmful phase transformation stresses, and obtain more ideal material microstructures and mechanical properties. It is necessary to strengthen the fundamental theoretical research on phase transformation behavior, develop advanced phase transformation control technologies, and promote the widespread application of high-temperature ceramic materials in key fields such as aerospace, energy, and national defense, providing material support for the development of high-end equipment manufacturing and strategic emerging industries. With the rapid development of modern information technology, the information wave characterized by digitalization, networking, and intelligence is profoundly transforming the industry by enabling the transition toward smart weaving systems and automated fiber processing. This digital evolution is redefining how manufacturers optimize production parameters and manage high-precision machinery to meet the demands of a connected global market.

AUTHOR CONTRIBUTIONS

Xianlong Wang designed, collected and analyzed the data, and drafted the manuscript. Xianlong Wang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Xianlong Wang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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