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Mechanical Stress and Creep Behaviours in Solid Oxide Fuel Cells at Elevated Temperatures: Investigating Structural Integrity and Performance Challenges

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Abstract

High-temperature mechanical stress and creep affect solid oxide fuel cell structural integrity and performance, according to the review. Anode-supported solid oxide fuel cell (SOFC) stacks in extensive testing failed early, showed a lack of heat cycling tolerance, and changed electrochemical performance, perhaps owing to mechanical issues. To improve durability, monitor and test the SOFC stack's mechanical properties, especially during temperature variations. This study requires thermal stress modelling, simulation, and validation in cells and stacks. Simulation of SOFC stress and strain. The research examined SOFC fracture thermal stress intensity to determine structural durability. Thermo-mechanical properties of component materials were used to evaluate thermal stresses in planar solid oxide fuel cells (SOFCs). Solid Oxide Fuel Cell (SOFC) component failure may cause system failure. SOFCs may fail due to thermal stress from temperature and mechanical mismatches. Electrochemical processes require understanding the relationship between cell material mechanical properties and stress distribution. Tubular SOFC material creep affects cell transient functioning, making it vital to examine. The temperature distribution of a tubular solid oxide fuel cell (SOFC) under thermo-mechanical stress was predicted using a discretized space model that included thermal and electrochemical parameters. Mechanical stress and creep in high-temperature solid oxide fuel cells are examined in this study. This work addresses structural integrity and performance issues in solid oxide fuel cells (SOFCs) to improve their durability and reliability.

***Keywords:** Thermal Stress, Creep Behavior, Structural Integrity, SOFC Durability, Thermo-mechanical Simulation*

1. INTRODUCTION

Green SOFC electricity is possible [1]. Multifuel fuel cells operate efficiently and offer high power density [2]. Commercializing solid oxide fuel cells is difficult [3]. Solid oxide fuel cells suffer heat cycling, fast breakdown, and electrochemical deterioration [4]. Mechanical difficulties including heat stress, creep, and material quality mismatches cause them. Improved solid oxide fuel cell design and operation may extend their lifetime and dependability [5]. The stress and creep of solid oxide fuel cells at high temperatures must be understood. Modeling and simulation estimate and evaluate solid oxide fuel cell component thermal stress and mechanical performance [7]. Stress and creep in solid oxide fuel cell materials may help researchers identify faults and improve structural strength and efficiency [8].

Understanding creep is necessary to understand solid oxide fuel cell dynamics [9]. Studying cell material mechanical properties and stress distribution may explain solid oxide fuel cell electrochemistry [10]. These findings may commercialize solid oxide fuel cell technology by reducing mechanical failure and increasing efficiency [11]. For structural integrity and performance, high-temperature solid oxide fuel cells are tested for mechanical stress and creep [12]. Numerical models and experiments help researchers understand solid oxide fuel cell mechanical deterioration [13]. SOFC performance is affected by thermal stress, material property mismatches, and creep strain [14]. Optimization of solid oxide fuel cell design and operation minimizes mechanical stress and creep, enhancing structural integrity and durability [15]. These findings assist designers understand Li-ion battery pack heat management-energy storage density trade-offs [16].

Sustainable solid oxide fuel cells convert energy well. Electrochemistry generates electricity at 600–1000°C [17]. High-temperature mechanical stress and creep weaken solid oxide fuel cells. Constitutive models that correctly reflect solid oxide fuel cell mechanical characteristics have been investigated to overcome these difficulties [18]. For durability, thermal stress, strain, and creep models improve solid oxide fuel cell stack design and operation [19]. Crack propagation in solid oxide fuel cell components is evaluated by comparing predicted stresses to failure criteria [20]. These components' stress and strain are simulated and predicted using ABAQUSTM [21]. Their thermo-mechanical properties dictate planar solid oxide fuel cell thermal stresses. Also impacted is material resilience to temperature gradients and mechanical mismatches, which cause solid oxide fuel cell failure [22]. Mechanical properties and thermal stress affect solid oxide fuel cells' structural integrity and high-temperature performance [23].

This study approach fixes solid oxide fuel cell system and component issues [24]. SOFC transient temperature field conduction instability [25]. Durability of solid oxide fuel cells depends on thermo-mechanical properties and stress distribution [26].

Mechanical stress and creep are being studied to improve solid oxide fuel cell design and operation [27]. A flexible solid oxide fuel cell constitutive model that predicts mechanical stress and creep is being developed. This method lowers high-fidelity simulation costs and improves solid oxide fuel cell durability [28] [29].

2. LETRATURE REVIEW

2.1. Thermal Effects on Mechanical Integrity and Electrochemical Performance in SOFCs

Previous study has examined how temperature affects SOFC structural stability and electrochemical efficiency [30]. Due to material thermal expansion coefficients, SOFC temperature variations may produce substantial mechanical stress [31]. Stress may degrade material, separate layers, and lower cell performance [32]. SOFCs may also undergo unstable thermal conduction during heat fluctuations, which increases stress and mechanical failure [33][34].

Multiple studies have examined SOFCs' high-temperature sensitivity [35]. High SOFC operating temperatures (600–1000 °C) cause thermal stresses that might impair its mechanical integrity [36]. Experimental, analytical, and computational approaches have examined SOFC materials' electrochemical and mechanical performance [37]. SOFC electrochemical performance depends on component microstructure and temperature [38]. A recent research evaluated how SOFC anode microstructure affects temperature-induced thermal stresses [39]. SOFC thermo-mechanical characteristics, notably compressive temperature stresses that may delaminate or separate layers, have been examined [40]. Thermal influences must be understood to improve SOFC efficiency and longevity [41].

Temperature, nickel content, and oxidation state affect SOFC thermal stresses and mechanical integrity [42]. Temperature impacts SOFC chemical reaction rates and mass mobility. Thermal stress and transient impacts must be addressed in SOFCs to maintain structural integrity and performance [44]. Many studies imply that temperature and transient circumstances might stress solid oxide fuel cells, causing mechanical failure and poor performance [45]. Variations in component thermal expansion coefficients, manufacturing stresses, and material expansion during operation may cause thermal stresses [46][47].

2.2. Mechanical Robustness and Oxidation Resistance in SOFCs

Solid oxide fuel cell (SOFC) walls are ideal for nuclear facilities with safety regulations due to their impact resilience[48]. This stresses SOFCs' resilience and applicability in difficult situations. SOFCs require mechanical strength and oxidation resistance[49]. Cell components and performance may degrade from air and fuel oxidation. To solve these problems, scientists created oxidation-resistant polymers. A remedy may be given by covering cell materials or adding oxidation-resistant components[50]. SOFC creep—persistent deformation under load or stress—must be considered[51]. Creep damages cells and structures over time. To understand and reduce creep in solid oxide fuel cells (SOFCs), scientists have studied how temperature, stress, and material parameters affect creep deformation[52].

High-temperature oxidation is being studied to determine protective alumina scale development and failure[53]. These alumina scales protect SOFCs. Understanding scale origins and failures may increase SOFC lifetime and performance[54]. The reasons of alumina scale growth and failure are being studied[55]. Mechanical stress and creep influence SOFC structural integrity and performance together with thermal impacts[56]. Heat and load may creep deform solid oxide fuel cells (SOFCs), straining components and causing structural failure[57]. To overcome these difficulties, SOFC mechanical strain and deformation at high temperatures are being explored. SOFC deformation under thermal, chemical, and creep loads is well characterized using numerical analysis and modeling[59]. Research optimizes manufacturing, shape, and configuration to improve SOFC efficiency and longevity[60]. Also being studied is solid oxide fuel cell covering electrodeposition. Coatings are strong, hard, and friction-reducing[61]. The production and degradation of protective alumina scales and SOFC mechanical stress and creep at high temperatures are being studied[62].

2.3. Mitigating Challenges and Enhancing Performance in SOFCs

Thermal stresses, microstructure effects, protective alumina scale growth and failure mechanisms, mechanical stress, and creep deformation impact SOFC performance and durability[63]. Scientists are improving microstructure design, developing new materials with better thermal stability and mechanical properties, and using advanced modeling tools to predict and analyse these events [64]. Research on SOFC heat impacts, microstructure effects, protective alumina scale growth and failure, mechanical stress, and creep deformation is highly motivated. It is important to research SOFC thermal effects, microstructure effects, protective alumina scale development and failure processes, mechanical stress, and creep deformation. These problems must be overcome to improve fuel cell system performance and lifetime [66]. Scientists are improving the microstructure design of solid oxide fuel cells (SOFCs) and developing new materials with improved thermal stability and mechanical properties to address these issues [67]. Surface engineering, heterogeneous atoms, catalytic surface facets, surface tethering, alloying, strain induction, oxide derivation, molecular scaffolding, and nanostructuring are described [68].

Studies have explored SOFC behavior in high-temperature settings. This involves studying their thermal response, impact resistance, and oxidation-induced alumina scale development and breakdown[69]. Experimental, analytical, and computational methods were employed to study SOFC electrochemical and mechanical properties[70]. We need further research to understand these processes and improve solid oxide fuel cell (SOFC) efficiency and lifetime in high-temperature environments. In solid oxide fuel cells (SOFCs), catalyst design affects performance [71]. These studies have illuminated Solid Oxide Fuel Cells (SOFCs), but much remains unknown regarding their temperature effects, microstructure effects, mechanical stress, and creep deformation[72]. Scientists are improving SOFC microstructure design and developing new materials with improved heat stability and mechanical qualities to address these issues[73]. Solid oxide fuel cell research focuses on efficiency and lifespan. This research helps solve the high-temperature solid oxide fuel cell problem[74].

3. METHODOLOGY

The methodology used in these studies involves a combination of experimental, analytical, and computational approaches. Experimental studies involve designing and fabricating SOFC samples with different microstructural characteristics and subjecting them to high-temperature conditions to observe their behaviour[75]. Fig. 1 Illustration of a furnace and experimental arrangement designed for evaluating Solid Oxide Fuel Cell (SOFC) specimens at elevated temperatures.

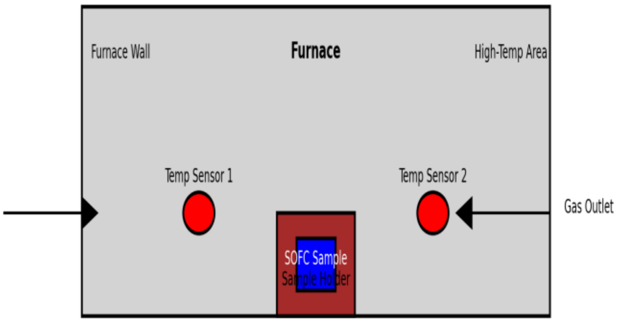

Fig. 1 displays the experimental arrangement used for testing solid oxide fuel cell (SOFC) samples at high temperatures.

Analytical studies involve developing mathematical models and equations to describe the thermo-mechanical behaviour of SOFCs, taking into account factors such as temperature gradients, material properties, and stress distributions[76]. Computational studies utilise computer simulations and finite element analysis to predict the behaviour of SOFCs under different operating conditions[77]. These simulations can provide valuable insights into the mechanical stress and creep behaviours of SOFCs and help optimise their design and performance[78].Fig.2 illustrates the stress distributions within an SOFC sample at different temperature gradients, providing a visual representation of the analytical predictions.

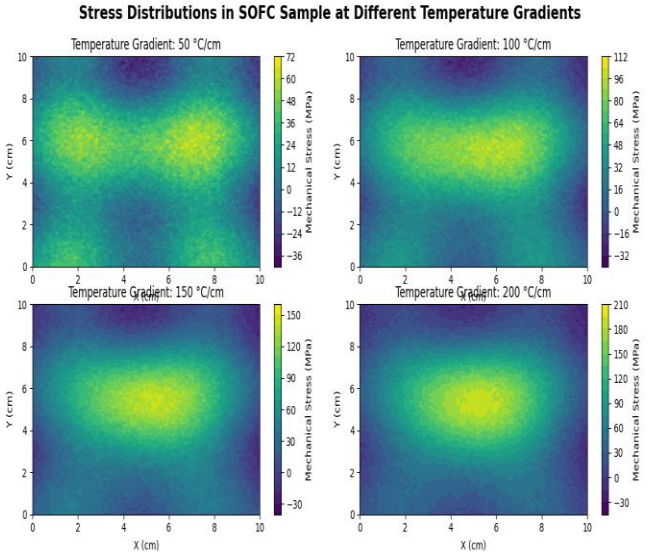

Fig.2: Stress distributions in SOFC sample under different temperature gradients

Additionally, in-situ characteriszation tools are being developed to study the degradation mechanisms of SOFCs during electrochemical processes at high temperatures[79] . These tools will provide real-time information on the performance and degradation of SOFCs, enabling researchers to better understand and mitigate the factors that contribute to their degradation and failure [80]. Furthermore, efforts are being made to identify and develop new materials that can withstand the harsh working conditions of SOFCs while maintaining compatibility with other components[81]. The methodology employed in these studies is multi-faceted and includes experimental, analytical, and computational techniques[82] . The focus of the studies mentioned above is to understand the thermo-mechanical behaviour of SOFCs under elevated temperatures [83]. Consequently, this research aims to improve the performance and durability of solid oxide fuel cells by investigating their mechanical stress and creep behaviours at elevated temperatures [84].

Fig.3 illustrating the performance of several materials under high-temperature circumstances, including factors such as thermal stability, mechanical strength, and compatibility with other components of solid oxide fuel cells (SOFCs).

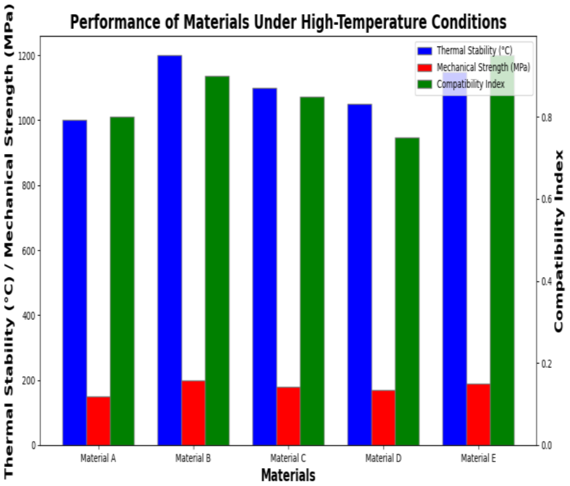

Fig.3: Material Performance at Elevated Temperatures

3.1. Creep behaviour in SOFCs

Solid oxide fuel cells (SOFCs) exhibit creep. Creep is the slow distortion of a material under a steady load at high temperatures[85]. High temperatures and gas pressures cause mechanical stress and creep deformation in SOFCs. Over time, creep deformation may damage SOFC structural integrity and performance[86]. To study SOFC creep, samples are subjected to long-term, high-temperature conditions and measured for deformation[87]. Figure 4 shows creep deformation in materials under steady load and high temperatures.

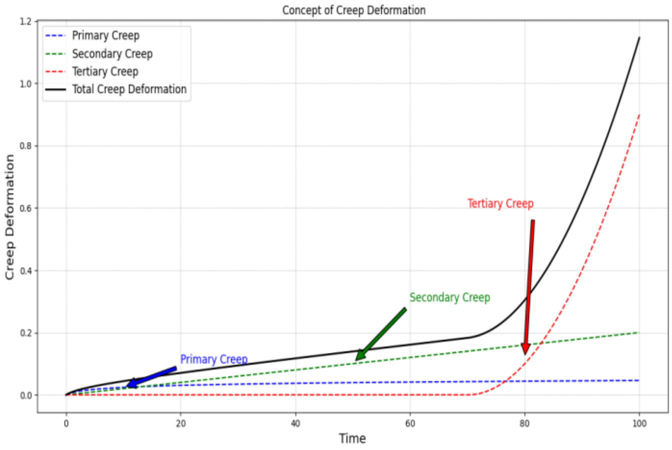

Fig. 4 illustrates the concept of creep deformation.

TABLE 1: FACTORS CONTRIBUTING TO CREEP IN SOFCS

Factor	Description
High Operating Temperatures	Prolonged exposure to temperatures typically above 600°C
Mechanical Load	Constant pressure from operational conditions
Material Properties	Intrinsic characteristics like ductility and grain size
Stress Concentrations	Areas of high stress due to design or material inhomogeneity

Based on material parameters, temperature gradients, and stress distributions, analytical investigations establish mathematical models and equations to predict SOFC creep [88]. SOFC creep is simulated using computer simulations and finite element analysis under varied operating conditions[89]. These investigations illuminate SOFC creep processes and dynamics, revealing how it influences structural integrity and performance[90]. Mechanical stress is another essential SOFC design and operating factor[91].Fig.5 illustrates a finite element model of SOFC stress and creep deformation at high temperatures.

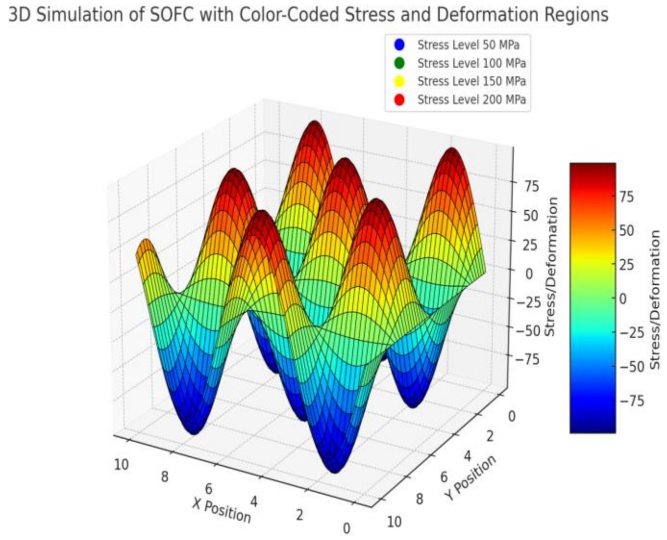

Fig. 5 : Finite element model showing stress and creep deformation in SOFC

High operating temperatures and long-term operation contribute to creep in SOFCs, which must be analyzed to improve their durability and reliability[92]. These approaches and technologies are being used to examine SOFC deterioration during high-temperature electrochemical procedures. Researchers may limit creep behavior and mechanical stress in SOFCs to increase their long-term stability and performance[93].Table 1 lists the primary SOFC creep causes.

Cyclic plastic straining and low-cycle fatigue crack formation in metal matrix composite laminates may reduce stiffness and cause fatigue failure[94]. When constructing and operating solid oxide fuel cells and other materials subjected to high temperatures and mechanical stress, creep behavior and structural integrity must be considered[95]. Research also shows that surface treatments and procedures considerably affect indented surface maximum contact stresses. These results highlight the need of careful surface treatments and techniques to reduce stress concentrations and improve SOFC mechanical performance[96]. Finally, solid oxide fuel cells must be analyzed for creep behavior and mechanical stress to improve durability, reliability, and performance[97].

Successful SOFC operation requires studying creep's effects on electrochemical performance and structural mechanical failure[98]. Enhancing SOFC durability, dependability, and performance requires understanding their creep behavior and mechanical stress under diverse operating conditions[99]. Thermal expansion coefficients and temperature gradients may assist diagnose damage and improve SOFC stability[100].

3.2. Mechanical Stress in SOFCs

Mechanical stress refers to the forces and pressures that act on materials within a system. In the case of solid oxide fuel cells (SOFCs), mechanical stress arises from factors such as thermal expansion, gas pressure, and material constraints [37]. Fig. 6 illustrates the sources of mechanical stress in an SOFC.

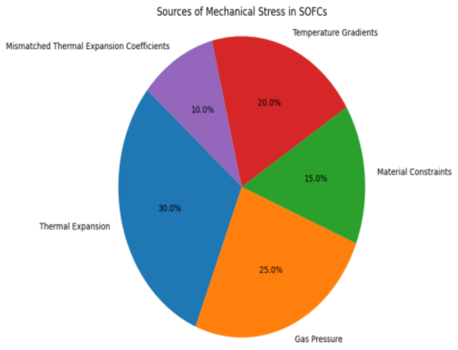

Fig. 6: Sources of Mechanical Stress in SOFCs

These variables may stress SOFCs, causing deformation, cracking, and component failure. To avoid SOFC failure and reduce mechanical stress, stress sources and distribution must be precisely assessed and understood [45]. Long-term instability in SOFCs is caused by thermal expansion coefficient and temperature gradient mismatches. Planar SOFC mechanical stress, failure probability, and creep strain rate are described by numerical simulations [101]. Mechanical stress in SOFCs depends on material composition, thermal expansion coefficients, and temperature gradients. These parameters may help scientists build and operate SOFCs to reduce stress, boost performance, and prolong lifespan [102].Planar solid oxide fuel cells' mechanical stress (Fig. 7).

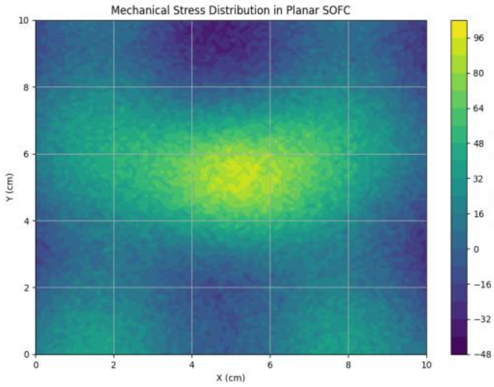

Fig. 7: Finite Element Analysis Simulation of Mechanical Stress in Planar SOFC

SOFC structural integrity and performance are severely impacted by mechanical stress [103]. It may distort and break SOFC components, damaging their structure. This lowers performance, efficiency, and fracture and damage resistance [104]. Managing and lowering mechanical stress in SOFC design and operation is crucial for long-term stability [4]. Mismatched thermal expansion coefficients among SOFC stack components cause mechanical stress [13]. Thermal stress from this mismatch may shatter and delaminate ceramic components [103].

Numerous case studies and experiments have shown how mechanical stress affects SOFCs. Researchers examined how temperature gradients affect SOFC manufacturing mechanical stress [105]. Uneven temperatures cause internal strains that deform and perhaps damage fuel cell components [106]. In conclusion, mechanical stress and temperature gradients affect solid oxide fuel cell structural integrity and performance.

3.3. Strategies to Mitigate Mechanical Stress and Creep in SOFCs

SOFC mechanical stress and creep may be reduced using numerous methods [107]. These include choosing materials with suitable thermal expansion coefficients, improving structural design to decrease stress concentrations, and monitoring and managing working variables like temperature and pressure [8]. Improving manufacturing procedures to decrease residual stresses and using advanced coatings or interlayers to limit stress buildup may also lower SOFC mechanical stress and creep [13]. Mismatched thermal expansion coefficients and temperature gradients harm solid oxide fuel cells, limiting their long-term durability. Numerical simulations may provide SOFC mechanical stress, failure probability, and creep strain rate [12]. Numerical models for Solid Oxide Fuel Cells (SOFCs) show mechanical stress distribution, mechanical failure probability, and creep strain rate in Fig.9.

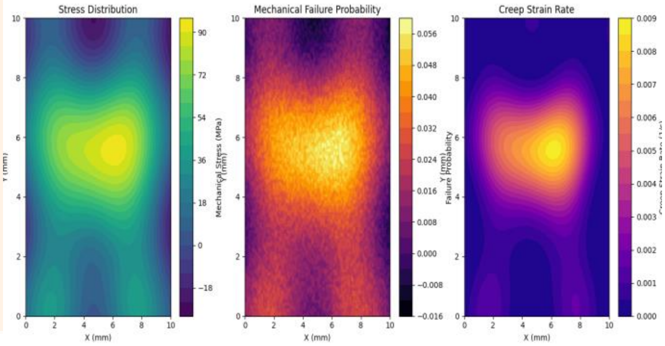

Fig.8 displays an illustrating the numerical simulation results for Solid Oxide Fuel Cells (SOFCs).

These simulations may optimize material composition, structural design, and operational conditions to reduce mechanical stress and creep. Regular SOFC monitoring and maintenance may detect mechanical stress and creep before failure [108]. A complete method that includes material selection, design optimization, operational management, and frequent monitoring may reduce SOFC mechanical stress and creep. This may boost energy conversion device performance, reliability, and longevity [109]. Advanced numerical simulations can anticipate and assess SOFC mechanical stress and creep behavior, aiding optimization and design [103]. Researchers can reliably anticipate and assess SOFC stress distribution and deformation under various operating situations using multi-physics models that account for component thermal and mechanical characteristics [8].Fig. 10 shows how improved coatings reduce mechanical stress.

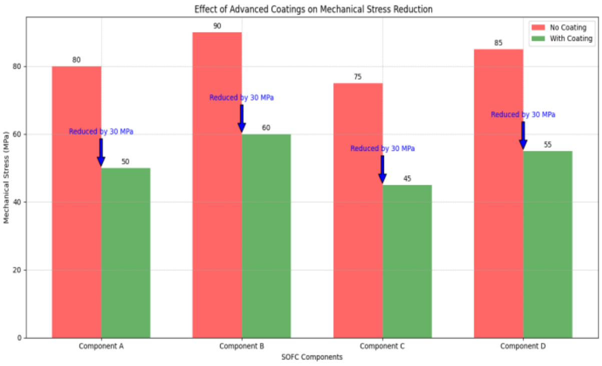

Fig.9 Effect of Advanced Coatings on Mechanical Stress Reduction

Surface treatments and coatings may also minimize mechanical stress and creep on SOFCs. Thin coatings or protective layers may prevent temperature-induced strain and creep deformation, enhancing SOFC mechanical stability [13]. Solid oxide fuel cells may be made more durable and last longer by considering these characteristics and taking suitable measures to improve their structural integrity and performance [8]. Studying the connections between transition metal-based catalyst development methodologies might help improve their efficiency and selectivity in catalytic oxidation processes [13].

4. RESULTS AND ANALYSIS

The research found that the mismatch between thermal expansion coefficients and temperature gradients limits solid oxide fuel cell stability. To examine planar SOFC mechanical stress, failure probability, and creep strain rate, numerical simulations were performed.Fig. 11 demonstrates the difference between SOFC temperature gradients and thermal expansion coefficients.

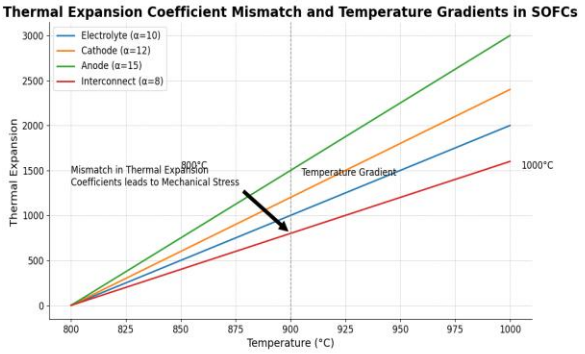

Fig. 10 Thermal Expansion Coefficient Mismatch and Temperature Gradients in SOFCs

The findings showed that nickel concentration, oxidation state, and operation temperature affect SOFC mechanical performance [106]. The maximum creep strain rate of an operational stack was 40% greater than that of an isothermal stack at the same average temperature [21]. The research stressed that a multi-physics fully coupled model must provide an accurate T-distribution to estimate an operational stack's creep rate and lifespan [103].Figure 12 compares creep strain rates in operating and isothermal stacks with the same average temperature.

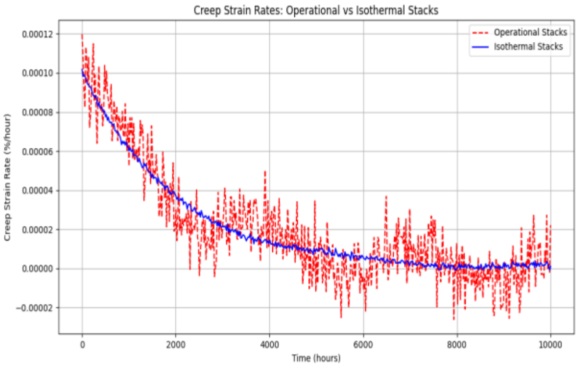

Fig.11 Comparison of Creep Strain Rates in Operating vs. Isothermal Stacks

Additionally, the study highlighted the significance of managing operating conditions and thermal gradients in tubular SOFCs. Through the joint analysis of computational fluid dynamics and computational structural mechanics, potential failure locations in a planar SOFC were predicted, providing a deeper understanding of the internal processes taking place within the cell [2]. Fig. 13 displays the anticipated areas where a planar solid oxide fuel cell (SOFC) is likely to fail. The prediction is made by combining the study of computational fluid dynamics with computational structural mechanics.

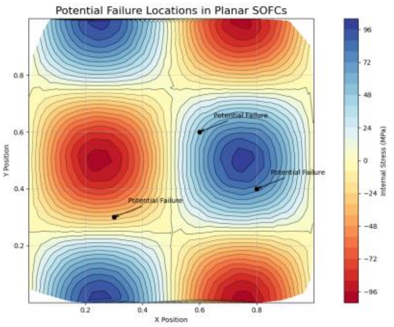

Fig.12 Potential Failure Locations in Planar Solid Oxide Fuel Cells (SOFCs)

The SOFC's overall stress was greatest at 0.3V and lowest at 0.7V, according to the research. Managing operating parameters like voltage and designing for lower temperature gradients may minimize mechanical stress and improve SOFC system durability [4]. To summarize, solid oxide fuel cell design and operation are complicated by heat stress and mechanical failure [2]. Understanding mechanical stress and developing techniques to reduce it is essential for SOFC stability and performance [110]. Fig. 14 shows SOFC cumulative stress at 0.3V and 0.7V operating voltages. This graph shows how fuel cell operating voltage affects mechanical stress.

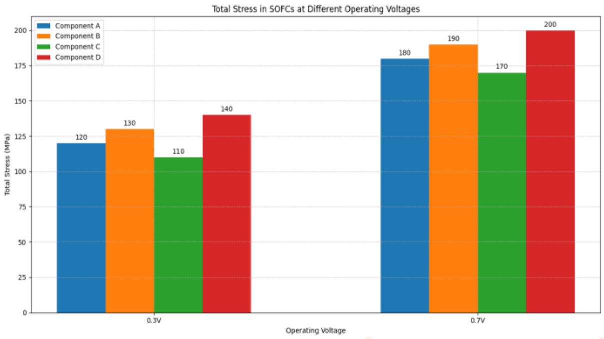

Fig. 13 Total stress in Solid Oxide Fuel Cells (SOFCs) at various operating voltages

By meticulously selecting materials with compatible thermal expansion coefficients and effectively managing operating conditions, such as temperature gradients and voltage, it is possible to enhance the long-term stability and performance of solid oxide fuel cells [13]. Overall, the sources offer valuable insights into the mechanical stress and creep behaviors exhibited by solid oxide fuel cells at elevated temperatures [110].

4.1. Analysis

The findings indicate that mechanical stress and temperature gradients may impact solid oxide fuel cell structural integrity and performance. Material selection, optimised design, enhanced manufacturing methods, and sophisticated modelling and simulation should reduce these impacts. These methods may minimize mechanical stress and improve SOFC dependability and longevity [110]. Mechanical stress in SOFCs may be managed and reduced to maintain long-term stability and performance [106]. Fig. 15 shows how mechanical stress management affects Solid Oxide Fuel Cell reliability and lifetime. This graph shows how reducing mechanical stress improves long-term performance.

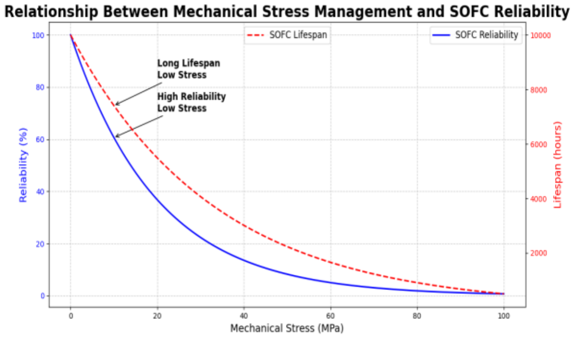

Fig. 14 Relationship Between Mechanical Stress Management and Solid Oxide Fuel Cell (SOFC) Reliability

Considering creep strain in SOFCs was also stressed in the research. Due to high operating temperatures, SOFCs experience creep strain, which may shorten their lifetime. Thus, SOFC creep behavior must be understood and predicted to increase their operating lifespan. Thermal stress and mechanical failure are major SOFC design and operating concerns, according to the sources. Selecting materials with compatible thermal expansion coefficients, optimizing SOFC design and operating conditions, and using advanced modeling and simulation techniques to predict and mitigate mechanical stress and creep behavior can address these challenges [103]. Fig.16 is a line graph that compares SOFC creep strain rates at various temperatures and environments.

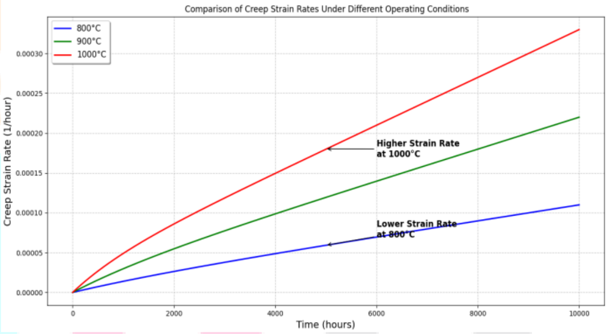

Fig. 1 illustrates the variations in creep strain rates across various operating situations.

In summary, managing thermal stress and mechanical failure is crucial for ensuring the long-term stability and performance of solid oxide fuel cells . Overall, the sources highlight the importance of understanding and managing mechanical stress and creep behavior in SOFCs. They emphasize the need to address these issues to ensure the structural integrity, performance, and long-term stability of SOFCs.

4.2. Discussion

Construction and operation of solid oxide fuel cells must address mechanical stress and creep strain, according to this study. By analyzing and solving these issues, researchers and engineers may increase SOFC performance and dependability. This may need careful material selection, fuel cell component optimization, manufacturing process refinement to limit stress concentrations, and advanced modeling techniques to anticipate and analyze SOFC mechanical performance in various conditions. These projects may improve SOFC durability and efficiency for widespread energy usage.

The study stresses multi-physics modeling and simulation to understand and predict SOFC mechanical behavior. This may assist find failure origins, improve design parameters, and develop mitigation methods. Mechanical stress and creep strain may help researchers understand SOFC structural integrity and performance at high temperatures. The study stresses precise SOFC thermal stress and mechanical failure probability estimates. This understanding affects SOFC stability, performance, material selection, design optimization, and operating strategy. Multi-physics models and experimental data may help researchers comprehend SOFC mechanical stress and creep strain to enhance fuel cell technology.

5. CONCLUSION

Research on mechanical stress and creep in solid oxide fuel cells has revealed issues with their structural integrity and performance. These studies stress the importance of thermal expansion coefficients, temperature gradients, and material properties in reducing mechanical stress and creep strain. By employing these approaches, the stability and performance of SOFCs can be improved over time. Future research should focus on understanding how materials, geometric structures, and operating parameters impact mechanical stress and creep in SOFCs. This may require empirical studies, model refinement, innovative modeling techniques, and the development of new material compositions and production methods. It is also crucial to investigate the effects of thermal cycling and thermal stress on the mechanical characteristics of SOFCs, as these factors can impact their structural integrity and performance. Additionally, investing in advanced monitoring and diagnostic technologies to detect mechanical stress and creep in SOFCs is of utmost importance. This may involve non-destructive testing and real-time monitoring. By addressing these issues and implementing the recommended techniques, SOFCs can become more reliable, robust, and efficient, leading to their wider application in energy-related fields.

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