Hindawi
International Journal of Aerospace Engineering
Volume 2023, Article ID 4465565, 16 pages
https://doi.org/10.1155/2023/4465565

Review Article

Review on Creep Phenomenon and Its Model in Aircraft Engines

Lin Yuan, Wang Chenglong, Sun Yongchao, Sun Mingbo, Yuan Yu, Gao Zhan, and Xiao Yiwen

College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China

Correspondence should be addressed to Lin Yuan; 3270383912@qq.com and Wang Chenglong; wangchenglong@163.com

Received 6 July 2022; Revised 10 May 2023; Accepted 15 May 2023; Published 29 May 2023

Academic Editor: E Jiaqiang

The aircraft is subjected to high-temperature and high-pressure conditions during flight, which renders it susceptible to the occurrence of creep phenomenon. Several academics have conducted extensive research on this issue. This research paper provides a comprehensive overview of the existing literature on creep phenomena in aircraft engines. First, several classical creep calculation models are enumerated and categorized as creep life calculation, creep-fatigue life calculation, and creep deformation calculation. Studies on creep phenomena are conducted in various components of aircraft engines, such as the engine's turbine blades, turbine disks, and combustion chambers. The creep behavior of turbine blades in aircraft engines has been extensively researched. Furthermore, the protective measures aimed at mitigating creep are presented. Materials with high creep resistance can be used, and alternative fuels could be implemented. This paper provides an in-depth analysis of the advantages of creep in aircraft, presented in a favorable perspective. Finally, the prospective future research direction is discussed.

1. Introduction

The phenomenon of creep occurs when a solid material experiences a constant external force, resulting in a time-dependent change in its stress and deformation. As a consequence, the relationship between the deformation, stress, and external force is no longer linear in nature. This deformation is irreversible even when the stress is lower than the yield limit [1]. Creep may happen at any temperature in materials including metals, minerals, and polymers. At low temperatures, the material's creep strain is negligible; nevertheless, with prolonged exposure to high temperatures, the creep deformation becomes too great to be disregarded. Figure 1 depicts the creep of gas turbine blades.

When an aircraft is in the atmosphere, many of its components are subjected to an extreme environment of high temperature and high pressure [2]. The turbine blades located within aircraft engines and high-speed rotating blades play a crucial role in drawing in high-temperature and high-pressure air into the burner to maintain engine operation [3]. The rocket engine combustion chamber is a device that facilitates the burning of fuel or propellant to produce high-temperature gas, and it is exposed to a high-temperature environment for an extended period [4]. The flight process of hypersonic vehicles involves extremely high speeds, resulting in strong shock compression and viscous blocking of the gas surrounding the vehicle, leading to the formation of a high-temperature and high-pressure aerodynamic thermal environment [5]. Figure 2 displays the X-43A aircraft, which was developed by NASA. Compared to conventional structures, aircraft engines are subjected to a harsher operating environment. For instance, a car engine's normal operating temperature ranges from 85 to 105°C, while the entire structure of the scramjet engine will be subjected to extremely high temperatures during operation. When the flight speed is six times the speed of sound, the combustion chamber temperature reaches approximately 2700 K, while the inlet temperature reaches 1500 K. In general, creep deformation occurs when the temperature is within the range $0.3T_m < T < T_m$ (where T_m is the melting point temperature of the material and T is the ambient temperature) [6]. When aircraft engines are subjected to high temperatures for an extended period of time, creep deformation will continue to accumulate, resulting in significant structural modifications before use. Hence, comprehending the creep behavior of aircraft under high-temperature and

Figure 1: The failure of gas turbine blades due to creep [2].

Figure 2: X-43A hypersonic flight vehicle [7].

high-pressure extreme conditions and employing a suitable creep theoretical model to anticipate creep deformation and creep life are crucial for ensuring aircraft flight safety.

Review articles about creep have been produced by scholars. Athul et al. [8] presented a summary of the many different creep deformation processes that are prevalent in magnesium alloys when exposed to increased temperatures due to the impact of elemental additions. In the article by Blum et al. [9], a simple model based on the Orowan equation and the dynamic evolution of the dislocation structure by generation and merging of slipped areas is used to determine which experimental results on creep of pure and solute-hardened crystalline materials can or cannot be explained in terms of creep with refinement or coarsening of the dislocation structure and steady-state creep. Sherby and Burke [10] investigated the mechanical properties of crystalline materials under extreme heat conditions. This paper provides a comprehensive review of the creep phenomena and creep calculation models in the context of aircraft. The first section presents the complete text's substance and leads to the article's main theme: creep. The subsequent section presents various conventional models for computing creep. Following generations predominantly employ the classical model and the enhanced classical model for the computation of aircraft component creep. The third section provides a summary of the creep exhibited by various components of an aircraft, such as turbine blades, turbine disks, and combustion chambers. The fourth section presents strategies aimed at mitigating the phenomenon of aircraft creep during flight. The fifth section elucidates the advantageous aspects of creep in aircraft, specifically its implementation, from an optimistic perspective. The observation can be made that creep possesses certain positive attributes. The creep phenomenon can be studied and utilized to accomplish specific objectives. The concluding section provides a summary of the entire text and outlines potential avenues for future research.

2. Creep Model

The phenomenon known as creep was initially introduced in Andrade's scholarly publication and has been a subject of study for over a millennium [7]. Currently, there exist three primary categories for the study and implementation of creep calculation. There are three approaches to consider in the analysis of creep behavior. The first involves providing the constitutive relation between stress and strain during the creep process and subsequently determining the creep deformation through the application of the finite element method. The second approach entails the direct calculation of creep life using the endurance equation. Lastly, the third approach involves calculating the fatigue life of creep.

2.1. Creep Constitutive Relation. The three common models for creep are the power-law model, Kachanov-Robotnov constitutive equation, and Lemaitre constitutive equation.

2.1.1. Power-Law Model. The power-law model is a type of creep model that is implemented in commonly used commercial software packages, including ABAQUS. The power-law model comprises two distinct forms, namely, the time hardening form and the strain hardening form. The time hardening form is a theoretical model that is grounded on the principles of time hardening theory, as documented in reference [6]. According to the theory, the reduction in creep rate observed during the creep process is attributed to material hardening due to time, rather than the result of creep deformation. The theoretical formula is

$$\dot{\varepsilon}_c = Am\sigma^n t^{m-1}, \tag{1}$$

where $\dot{\varepsilon}_c$ is the rate of change of creep strain; A, m, and n are the constants related to the material; σ is the stress; and t is the time.

The concept underlying the strain hardening form is that a phenomenon comparable to metal work hardening at room temperature and creep hardening during the creep process exists. The relationship between plastic deformation and creep has nothing to do with time. The theoretical formula [7] is

$$\dot{\varepsilon}_c \varepsilon_c^{\alpha} = \beta \sigma^m, \tag{2}$$

where α, β, and m are the constants determined by experiment.

The compression creep properties of aerogel were investigated by Xuefeng et al. [11] at both room temperature and high temperature, with consideration given to the characteristic load of thermal protection systems. The time hardening power-law model was utilized to model and validate the creep behavior. The findings suggest that the power-law model is a reliable predictor of the creep behavior of aerogel gel.

2.1.2. Kachanov-Robotnov Constitutive Equation. The constitutive equation of Kachanov [12] is founded on the continuous damage mechanic (CDM) [13] method. The utilization of continuous damage mechanic methodology involves the estimation of the fracture strain and failure time of high-temperature structures through the incorporation of constitutive equations and damage variables. One benefit of utilizing this approach is that it facilitates the numerical simulation of the progression of damage, while concurrently enhancing the precision of the local stress and strain field data. The equation that defines the relationship between the physical properties of a material and its deformation behavior can be represented as

$$\begin{aligned} \frac{d\varepsilon_{ij}}{dt} &= \frac{3}{2} A S_{ij} (\bar{\sigma})^{n-1} (1-\omega)^{-n}, \\ \frac{d\omega}{dt} &= B \frac{(\sigma_r)p}{(1+q)(1-\omega)q}, \quad \omega_c = 1, \end{aligned} \tag{3}$$

where ε_{ij} is the creep strain tensor; A, B, p, and q are the material constants; ω_c is the critical value of material damage; and σ_r is the creep rupture stress.

In their study, Wang et al. [14] made predictions regarding the rafting behavior of single crystal nickel-based alloys with varying orientations at a temperature of 950°C. A creep model for a single crystal nickel-based alloy was established by integrating the raft prediction results and crystal slip theory with the Kachanov-Robotnov damage evolution formula. The findings indicate that the model was able to make precise predictions regarding the raft type and the initial law of slip system of nickel-based single crystal alloy. This aligns with the underlying physical mechanism of creep deformation.

2.1.3. Lemaitre Constitutive Equation. The Lemaitre constitutive equation [15] is proposed based on the theory of irreversible thermodynamics. The constitutive equation can be expressed as

$$\begin{aligned} \omega &= 1 - \left[1 R_v (1+\alpha_0) \left(\frac{\bar{\sigma}}{g} \right) \right]^{1/1+\alpha}, \\ R_v &= 3(1+\upsilon) + \frac{3}{2}(1+2\upsilon) \left(\frac{\sigma m}{\bar{\sigma}} \right)^2, \end{aligned} \tag{4}$$

where α_0, g, and α are the material constants and υ is Poisson's ratio.

Wang and Guo [16] conducted continuous damage mechanic analysis and research on high-temperature creep and creep fracture behavior of high-temperature titanium alloy IMI834 for aeroengines operating at 650°C. The predictive analysis of the creep fracture life for uniaxial smooth round bar specimens was conducted using the Lemaitre constructive equation. Figure 3 displays the curve depicting the relationship between creep strain and time. The findings were in line with the experimental data, indicating that the constitutive equation had the capability to precisely predict the creep fracture lifespan of alloy steel.

The aforementioned model was developed beforehand and has since reached full maturity. In all fields, it is employed for the calculation of creep in materials.

2.2. Creep Life Calculation. Time-consuming is the process of establishing an accurate model to calculate the creep life under varying temperatures and stresses. Typically, the engineering method is used to calculate the creep life in practice. To calculate creep life, the Chinese national military standard (GJB/Z18-91) and the American military standard (MIL-5007D) recommend four types of persistence equations: the Larson-Miller equation, Ge-Dorn equation, Manson-Succop equation, and Manson-Hafere equation.

Larson-Miller equation:

$$\log t = c + \frac{b_1}{T} + \frac{b_2 x}{T} + \frac{b_3 x^2}{T} + \frac{b_4 x^3}{T}. \tag{5}$$

Ge-Dorn equation:

$$\log t = c + \frac{b_1}{T} + b_2 x + b_3 x^2 + b_4 x^3. \tag{6}$$

Manson-Succop equation:

$$\log t = c + b_1 T + b_2 x + b_3 x^2 + b_4 x^3. \tag{7}$$

Manson-Hafere equation:

$$\log t = c + (T - T_a)\left(b_1 + b_2 x + b_3 x^2 + b_4 x^3\right), \tag{8}$$

where c is the regression constant, t is the breaking time, T is the absolute temperature, x is the stress logarithm, and b_i and T_a are the coefficients related to material.

Yang et al. [17] demonstrated that the Larson-Miller parameter could accurately characterize the various aging behaviors of 12Cr1MoV, 15CrMo, and other materials used in main steam pipelines through a series of temperature-time combination laboratory simulation experiments and a comprehensive data analysis.

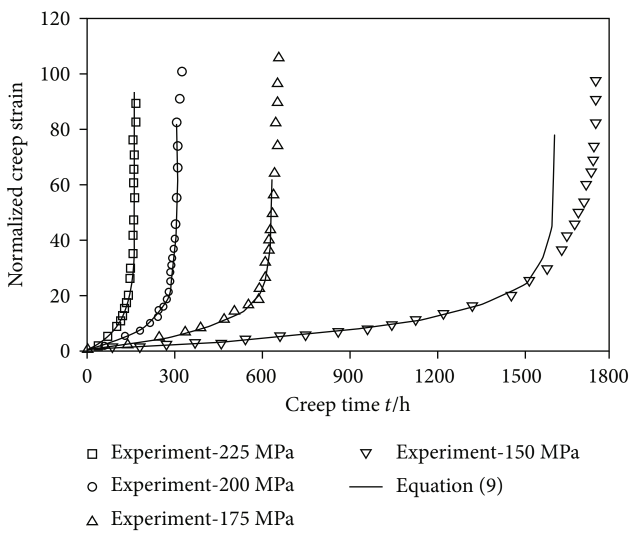


Figure 3: Variation of normalized creep strain with time t [16].

The engineering method for calculating creep life entails describing the fracture zone of potential components at low temperature and high pressure and medium temperature and medium pressure and the hazardous section at high temperature and low pressure, calculating the stress state and temperature, and then employing the unified persistence equation or life estimation test. This method does not account for the effect of the redistribution of stress during creep. The section can only be selected based on prior experience. When the section has a temperature gradient, it is difficult to analyze.

2.3. Creep-Fatigue Life. The fatigue of materials with a minor creep strain under alternating load is referred to as creep-fatigue. Different from fatigue, its failure mechanism is the coupling of multiple damage accumulation mechanisms. Under the interaction of creep and fatigue, the service life of parts is 1~2 orders of magnitude lower than that under pure creep and pure fatigue [18]. Therefore, interaction between creep and fatigue is frequently considered when contemplating creep. Below are some life prediction models for the creep-fatigue life interaction.

2.3.1. Ductility Exhaustion Method. Priest and Ellison [19] proposed the ductility exhaustion technique for the first time in 1981. According to the theory of ductility loss, the deterioration induced by creep and fatigue is not independent but rather interactive. In other words, creep and fatigue not only cause damage to materials separately but also interact with one another to enhance the degree of damage at high temperatures. Attaining a certain critical value will cause the material to fracture. The creep-fatigue estimation formula is as follows:

$$\sum_{r=1}^{N_c} \Delta\varepsilon_c = D_c, \tag{9}$$

where $\Delta\varepsilon_c$ is the increment of creep strain, D_c is the total creep, and N_c is the number of cycles.

Takahashi [20] calculated the total creep damage and total fatigue damage of the creep-fatigue test and predicted the fatigue life of the creep-fatigue test using this method. The results indicated that the creep damage value was high and that the ductility loss model provided a conservative estimate of the service life.

2.3.2. Robinson-Taira Method. Robinson and Taira put forward the high-temperature creep-fatigue linear cumulative damage formula [21]:

For constant amplitude load:

$$D = \frac{N}{N_f} + \frac{t}{t_R}. \tag{10}$$

For variable amplitude load:

$$\begin{aligned} \sum_{i=1}^{n} \frac{N_i}{N_{fi}} + \sum_{i=1}^{n} \frac{t_i}{t_{Ri}} &= D, \\ \varphi_c &= \sum_{i=1}^{n} \frac{t_i}{t_{Ri}}, \\ \varphi_f &= \sum_{i=1}^{n} \frac{N_i}{N_{fi}}, \end{aligned} \tag{11}$$

where D is the total damage, N is the number of creep-fatigue cycles, N_i are the number of pure fatigue cycles under the i-th amplitude load, N_{fi} are the total number of pure fatigue cycles under different amplitude loads, t is the creep cycle fracture time, t_{Ri} are the pure creep rupture time under constant amplitude load, t_i are the time of pure creep fracture under the i-th amplitude load, φ_c is the pure creep damage, and φ_f is the pure fatigue damage. When $\varphi_c + \varphi_f = 1$, the material is considered to fail.

On the basis of the reliability analysis of endurance life and Miner's linear cumulative damage theory, Yuanwei and Shan [22] assessed the reliability of low-cycle fatigue life of turbine disk taking creep damage into account.

Extensive research has been conducted by scholars on various components of aircraft engines, including turbine blades, turbine discs, and combustion chambers. The aforementioned models are presently prevalent in the field of creep analysis. Models that offer a direct constitutive relationship between stress and strain during the creep process enable the observation of creep deformation at any point in the calculation, thereby facilitating identification of the component's weak position. However, this approach is computationally intensive. The method of calculating creep life based on the endurance equation is practical and well-suited for engineering applications, but only the numerical value of creep life can be determined; structural changes cannot be determined. The calculation of creep-fatigue life takes fatigue into account, resulting in more accurate results, but structural alterations cannot be determined.

3. Review on Creep of Aircraft Components

The primary focus of researchers' investigations into aircraft creep pertains to components of aircraft engines. The following is a summary of the creep that varies among the various aircraft components.

3.1. Creep of Engine Turbine Blade. The aircraft engine turbine blade creep has been the subject of the most previous research. Creep-fatigue interaction life calculation and pure creep calculation comprise the blade research. In 1975, Majumdar [23] examined the creep of fan engine turbine blades for the calculation of creep-fatigue interaction life. He established a method for predicting low-cycle fatigue and creep damage, as well as the critical engine parameters to be monitored in conjunction with an on-board computer or a suitable recording system that can be used on a central computer at the conclusion of a flight. This calculation of creep life was not a singular calculation of creep life, but rather an interactive calculation of creep-fatigue life. First, the Manson [24] formula was used to compute the low-cycle fatigue life of the blade, followed by the damage law of linear creep-fatigue interaction [21] to calculate the final life. The results demonstrated that the creep life and stress fracture life of turbine blades were functions of blade average temperature and blade average stress that were directly proportional to the square of turbine speed. In Sabour's dissertation [25], a novel mathematical model for predicting the operational life of aircraft components (particularly gas turbine blades susceptible to creep-fatigue at elevated temperatures) was proposed, and its numerical and experimental evaluation was conducted. The Lagrange-Bhat method [26] was used to analyze the curve turning and flattening phenomena of rotating blades in a thermal environment, and a simple constitutive model of creep-fatigue interaction was proposed. Under complex creep-fatigue conditions, the model could be used to determine the life under pure creep lifetime and pure fatigue experimental results. The results indicated that the linear summation of creep and fatigue damages at modest strains provided an excellent prediction of creep-fatigue life. Through testing, Karpinos et al. [27] determined the residual thermal cycle creep and long-term strength life of used aviation gas turbine blade materials. The residual creep-fatigue life of a high-pressure turbine blade was determined by testing a used rotor blade for creep-fatigue. The used blades are depicted in Figure 4. The results indicated that the failure of the sample was caused by the material's thermal cycle creep. In addition, the regression equation for calculating the residual creep strain and long-term strength of materials was proposed based on the statistical analysis of the test data. The aforementioned information relates to how creep-fatigue interaction life is calculated.

Figure 4: The used blades [27].

In 1993, Vetrov and Kucher [28] conducted a creep analysis to determine the remaining lifespan of blades. Their methodology involved considering the accumulated creep strain and accounting for the impact of vibration loads. The integration of creep strains over the volume of a blade was used to determine its accumulated elongation. The gamma-percent life of blades was derived using the central limiting theorem. A revision was made to the calculated approximations based on blade elongation measurements taken during operation. Marahleh et al. [29] conducted research on the feasibility of forecasting the service life of gas-turbine blades composed of nickel alloys based on the outcomes of accelerated testing of specimens extracted from the blades. The present study employed the Larson-Miller parameter and Robinson's [30] rule to forecast the lifespan of the blade. The findings indicate that the Larson-Miller parameter model exhibited superior predictive capabilities with respect to blade longevity for durations below 80000 hours. In his study [31], Naeem projected that the creep life consumption of high-pressure turbine blades in turbofan aeroengines would increase or decrease depending on the daytime temperature. The researcher employed the Larson-Miller equation and Miner criterion to determine the creep life in the study. The findings indicate that the impact of temperature variation on the depletion of creep life of blades was noteworthy. In the subsequent year, Naeem and Ul-Haq [32] conducted a study wherein they chose the blade of the high-pressure turbine (HPT) as the focal point of their investigation. The HPT blade has emerged as a critical component of the turbine engine due to its exposure to the highest levels of gas temperature and speed. The present study elucidated the impact of corrosion on the consumption of creep life of high-pressure turbine blades. The primary modes of potential failure for turbine components include mechanical fatigue, thermal fatigue, oxidation, vulcanization, and creep. Among these, creep poses the most significant potential problem in high stress and high-temperature applications. The present study employed the Larson-Miller equation and Miner criterion to, respectively, forecast the creep life. The findings of the study suggest that the degradation of efficiency in a high-pressure turbine (HPT) has a negative impact on creep life, particularly when accompanied by corrosion of the turbine blades. Moreover, a higher level of deterioration in the HPT's flow capacity exacerbates this effect.

The article by Ejaz et al. [33] was distinct from previous articles, which analyzed a particular experimental phenomenon.

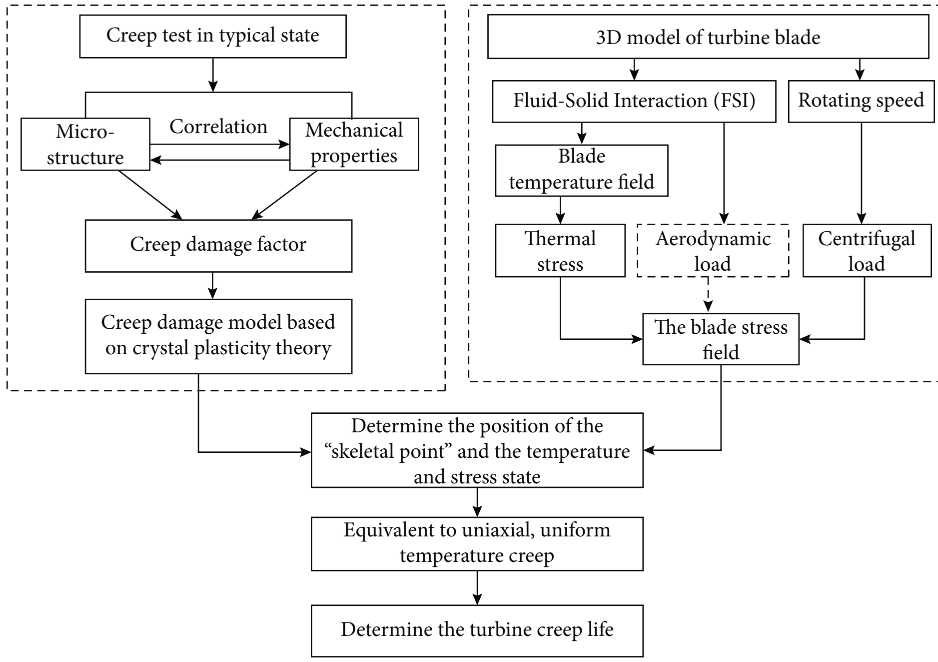


FIGURE 5: Prediction method of turbine blade creep life [38].

This paper investigates the fracture of a low-pressure turbine blade in an aircraft engine during ground testing. The study focuses on analyzing the failed blade and the adjacent nonfailed blade. The analysis of the blade's microstructure was conducted. This study examines the fracture of a low-pressure turbine blade in an aircraft engine during a ground test. The investigation reveals that the primary cause of the fracture was attributed to creep. In a recent study, Jianzhong and Hongfu [34] investigated the impact of engine performance degradation, atmospheric temperature fluctuations, and thrust reduction take-off on the creep life of turbine blades. This was achieved through the utilization of an engine performance simulation model and the Larson-Miller creep life prediction model. The study revealed that the degradation of engine performance had a notable impact on the lifespan reduction of turbine blades. Specifically, a mere 3% decline in compressor efficiency could lead to an 80% reduction in the creep life of turbine blades. Furthermore, the creep life of turbine blades exhibited an exponential decline as atmospheric temperature increased. While a decrease in thrust take-off had a discernible effect on extending the life of turbine blades, this effect became less significant as thrust was further reduced. Jahangiri and Abedini [35] conducted a study in the same year to investigate the impact of time use exposure on the microstructure and mechanical properties of gas turbine blades made from IN939 superalloy. The findings from the stress rupture experiments indicate that the duration of creep life for the alloy that was subjected to service exposure at 850°C was comparatively shorter than that of the new alloy. The observed phenomenon is believed to be caused by the deterioration of the alloy's microstructure resulting from its use in a gas turbine. The research conducted by Sixu [36] is considered to be innovative. The author utilized a BP neural network to forecast the creep life of engine blades. The input layer of the neural network was comprised of metallographic structure characteristic parameters, while the output layer was the predicted creep life. The findings indicate that the model exhibited a high degree of accuracy in forecasting the lifespan. The creep life of blades was assessed by Sahoo et al. [37] using stress fracture testing, while the damage to the coating was evaluated through coating expansion and secondary reaction zone (SRZ). This study investigates the impact of aluminum coating on the surface of a deformable alloy blade composed of nickel on both the creep life of the blade and the microstructure degradation of the blade during its service. The study determined that the reduction in creep life can be attributed to the deterioration of carbide morphology. Furthermore, the creep life is influenced by the dimensions, configuration, and dispersion of grain boundary carbide. Li et al. [38] developed a constitutive model for a material using microcrystalline plasticity theory and a macroscopic phenomenological model of creep. They conducted simulations of the creep behavior of three-dimensional blades and proposed a technique for determining the creep life of turbine blades using the skeleton point stress method, as depicted in Figure 5. The aforementioned pertains to the computation of the lifespan solely attributed to creep, excluding any contribution from fatigue. Numerous prior investigations have been conducted regarding the determination of blade pure creep life. However, the majority of these studies employ rudimentary life calculation methodologies, such as the Larson-Miller equation.

3.2. Creep of Engine Turbine Disk. The environment of high temperature and high pressure poses a risk of creep failure for the turbine disk and blade. Researchers have also analyzed turbine disk creep. Moreover, blade studies can be broken down further into two distinct subfields: pure creep calculation and creep-fatigue interaction life calculation. Mao et al. [39] collected fracture growth data of a high-

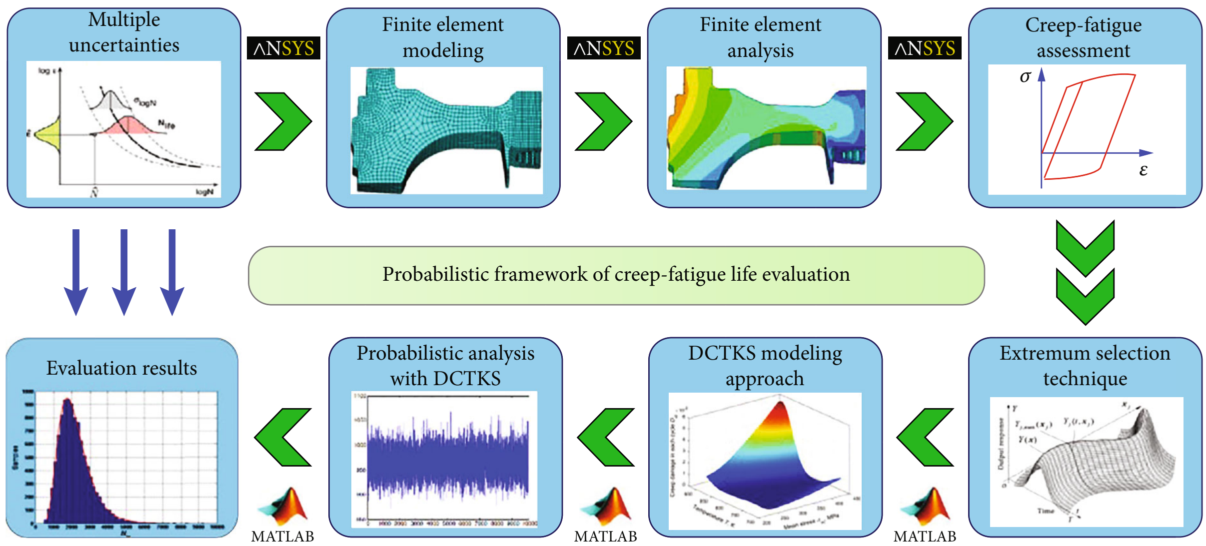
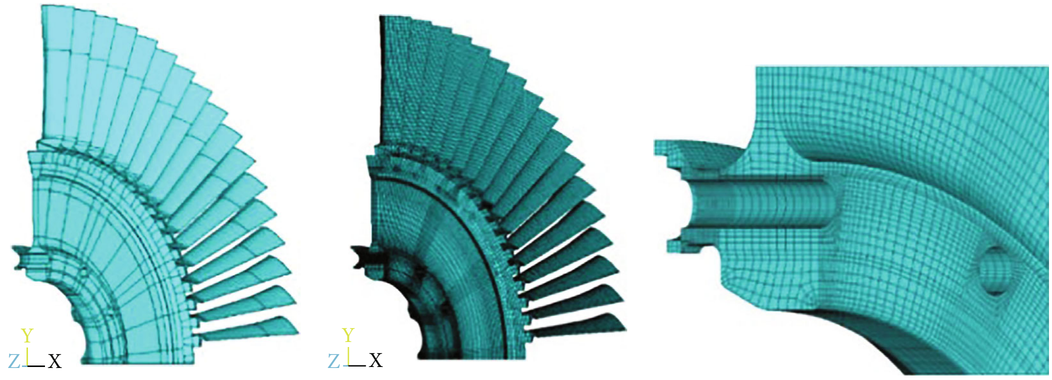


Figure 6: Probabilistic framework of creep-fatigue life evaluation [41].

temperature nickel-based superalloy subjected to both static and cyclic loading at high temperature in order to calculate the creep-fatigue interaction life. The turbine disk's stress was analyzed. Using creep-fatigue fracture growth data and the Paris equation [40], the residual life of turbine disk components at various temperatures and conditions was then estimated. The results of the life evaluation demonstrated that the concept of cause retirement could be utilized to determine the remaining life of turbine disks designed using the conventional fatigue life method. Using the probabilistic creep-fatigue life assessment of a typical turbine disk as an illustration, Song et al. [41] proposed a decomposed collaborative time-variant Kriging surrogate model (DCTKS) by incorporating the strengths of extremum selection technique and Kriging model into a decomposed collaborative strategy, as depicted in Figure 6. The results demonstrated that the author's proposed DCTKS method not only ensured acceptable calculation precision but also substantially increased calculation efficiency. It was an effective and efficient probabilistic life evaluation method for turbine disk creep-fatigue. In addition, sensitivity analysis revealed that the dynamic working load (rotor speed and body temperature) had the greatest influence on the creep-fatigue life of the turbine disk and thus should be given primacy in the probabilistic creep-fatigue evaluation of the turbine disk.

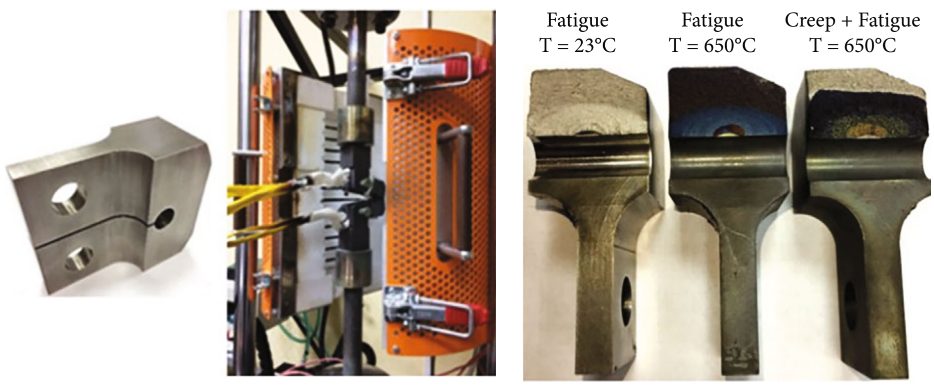
The low-cycle fatigue behavior and creep behavior were calculated by Shlyannikov et al. [42], utilizing the crack growth rate model formula [43] to analyze the elastic-plastic and undamaged/damaged creep crack tip field. The study is aimed at predicting the creep-fatigue crack growth rate and residual life of a GTE turbine disk subjected to various working loads and damage combinations. The findings suggest that the undamaged crack growth model, when compared with the continuous damage mechanic approach, exhibited an overestimation of the overall remaining lifespan of the turbine disk. Furthermore, the degree of error was observed to escalate with an increase in the duration of holding time. Runzi [44] proposed a modified strain energy density dissipation method with high precision. The method is based on the Takahashi model [45] and takes into account the recovery effect of compressive average stress. The present study employed a technique to assess the creep and fatigue degradation of a turbine disk in an aeroengine operating under conditions of steady-state cycling. The findings of the investigation revealed that the location of crack initiation due to creep-fatigue was typically at the point of geometric discontinuity in the structure. Shlyannikov et al. [46] performed a comprehensive three-dimensional finite element analysis on a standard gas turbine engine (GTE) turbine disk, as illustrated in Figure 7. The Norton constitutive equation was utilized to characterize the creep behavior of the material. The investigation focused on the stress-strain state and damage accumulation within the service critical zone. Experimental analysis was conducted to examine the surface crack growth rate under high-temperature harmonic loading, as well as block loading under fatigue and creep-fatigue interaction. These findings are depicted in Figure 8. The study revealed that when subjected to pure fatigue and creep-fatigue interaction load, every segment of the fatigue section exhibited a uniform curve in relation to nonlinear fracture resistance parameters, signifying the initial and subsequent stages of block loading progression.

Kaishang et al. [47] conducted an assessment of creep-fatigue damage and predicted the lifespan of structures with discontinuities using the cross-scale modeling approach. The present study is aimed at determining the hazardous position of discontinuous structure during the process of creep-fatigue by integrating the nonuniform cyclic constitutive equation and creep-fatigue damage model at the macro scale. Furthermore, the micro mechanical behavior and damage evolution law at the aforementioned hazardous position were elucidated with the aid of crystal plasticity theory at the micro scale. Porous structures underwent a series of creep-fatigue tests. The findings indicate that the anticipated lifespan for crack initiation was in agreement with the outcomes of the experiment. The present study utilized



(a) (b) (c)

Figure 7: GTE turbine disk model [46].



(a) (b)

Figure 8: Test equipment (a) and fracture surfaces (b) for simulation models [46].

a multiscale modeling approach to assess the damage of a specific turbine disk type. The methodology for multiscale modeling is depicted in Figure 9.

Pokrovskii et al. [48] proposed an empirical approach, known as the theoretical-experimental model, to estimate the mean rate of the initial segment of the creep crack growth curve for pure creep analysis. The aforementioned model was employed to make predictions regarding the rate of crack growth in structural alloys when subjected to the simultaneous effects of fatigue and creep. In their study, Osigwe et al. [49] conducted a comprehensive analysis of the impact of fuel heating values on the high-pressure turbine hot section's top-level creep life assessment. The utilization of the Larson-Miller equation persisted as a means of assessing the creep life. The present investigation demonstrated that the utilization of liquefied hydrogen fuel resulted in improved performance, specifically a 64% reduction in fuel flow rate and better specific fuel consumption (SFC). Additionally, the use of this fuel source was found to extend blade life by 15%. These findings are consistent with existing literature that highlights the advantages of liquefied hydrogen fuel over traditional jet fuel. In their study, Tomevenya and Liu [50] analyzed the fatigue creep of a turbine disk made of nickel-based superalloy GH4133 at 650°C. The researchers considered material characteristics, load, and performance parameters as random factors and conducted finite element analysis to investigate low-cycle fatigue. The LCF Manson-Coffin model was utilized to compute the fatigue life, while the Larson-Miller equation was employed to determine the creep life. The Robinson rule, also referred to as damage fraction summation, was employed to determine the low-cycle fatigue-creep life. This was subsequently modeled using a two-parameter Weibull distribution. The findings indicate that there was a decrease in reliability as the fatigue-creep life increased. In the realm of turbine disk research, there exist a limited number of instances wherein pure creep life calculation is conducted, with the majority of cases taking into account the concurrent impact of fatigue.

3.3. Creep of Combustion Chamber. The NASA Lewis Research Center conducted tests on small thrusters by Quentmeyer [51] and Jankovsky et al. [52] which revealed that the lifespan of the combustor was influenced by factors such as creep-fatigue interaction, corrosion, and occasionally ductile rupture, in addition to fatigue. Kasper [53] employed a methodology based on cyclic fatigue and creep analysis to make an estimation of the lifespan of the combustor. He noted that there was no general viscoplastic model that could account for all potential material behavior phenomena, so models for various materials and properties must be chosen. Sung et al. [54] designed and tested a small rocket

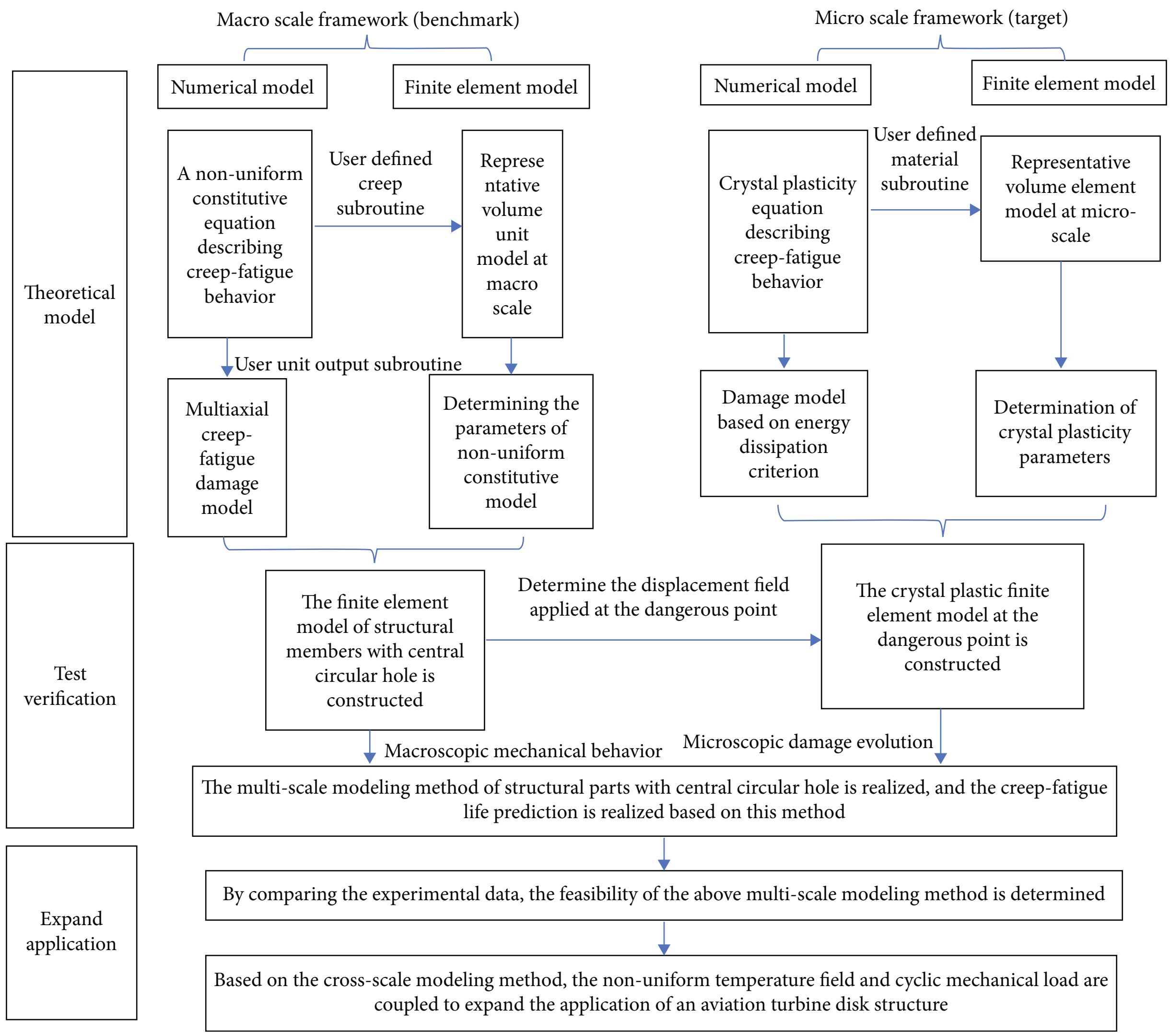


Figure 9: Process of multiscale modeling method [47].

combustor and validated the low-cycle fatigue and fatigue-creep interaction life prediction models. Figure 10 depicts the rocker combustor. This study utilized various life prediction techniques to forecast the lifespan of a combustion chamber, which were subsequently compared to experimental outcomes. The findings of the study indicate that the viscoplastic model [55] exhibited superior consistency in comparison to conventional techniques when forecasting life cycle failure in conditions of low-cycle fatigue and high temperature. The aforementioned text pertains to prior investigations conducted on the lifespan of combustion chamber in relation to creep-fatigue interaction.

Jaihyun [56] utilized ANSYS software to perform finite element modeling and creep-based stress analysis on the combustion chamber of a cryogenic engine. Figure 11 depicts the combustion chamber of the cryogenic engine. Using the Norton and exponential drift models, the total steady-state thrust duration of 7200 seconds (10 times the nominal operating time of 720 seconds) was analyzed. The analysis revealed that the effect of creep on the Cu-Cr-Zr-Ti alloy combustion chamber was negligible over an operational duration of 7200 seconds (10 times the nominal thrust duration of the engine), even at 126% increased thrust level. Both models of expansion yielded comparable results.

Zarubin et al. [57] conducted an analysis on the loading of shell wall connectors and the accumulation of inelastic deformation of inner wall materials. This analysis was based on a simplified analysis model of a bimetallic shell, which was used in a reusable liquid rocket engine combustion chamber. The study considered plastic deformation and creep deformation over time. The estimation of the number of operating cycles for the availability of the inner wall material was based on the assessment of the absolute values of the creep of the wall material and the accumulated inelastic deformation without creep in a single engine cycle. Masuoka and Riccius [58] devised a system based on damage mechanics that can properly mimic the damage propagation phenomena, which was utilized to model the damage propagation of rocket cabin materials. A viscoplastic model [59], a creep-fatigue model, and a ductile damage model [14] were combined with the model. Figure 12 illustrates a comparison between the numerical results and the actual

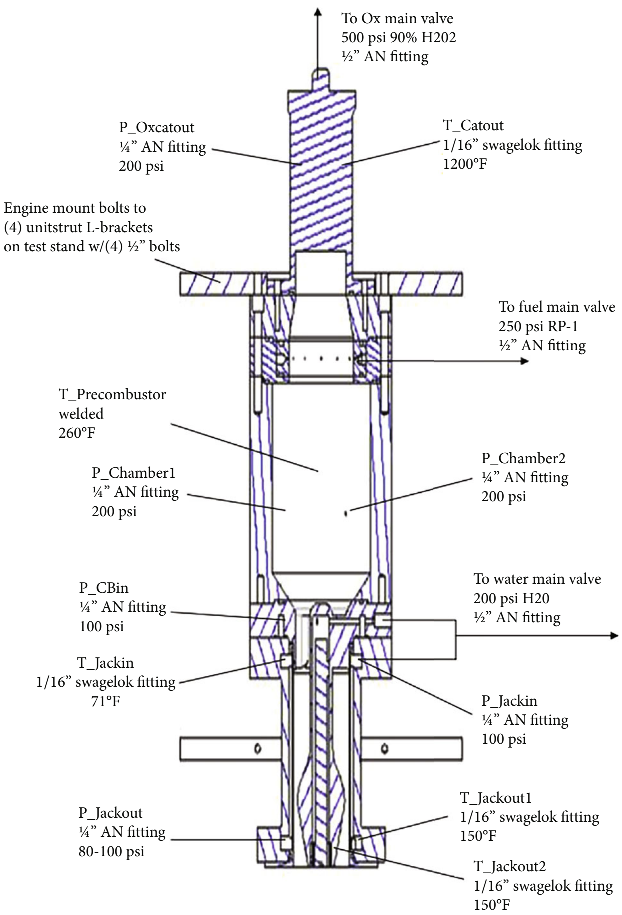


Figure 10: Small rocket combustor model [54].

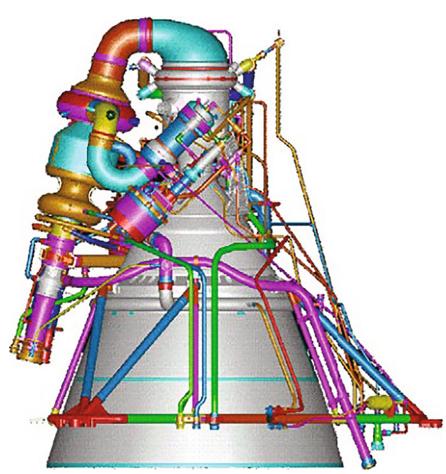


Figure 11: Cryogenic engine combustion chamber model [56].

deformation of the cooling channel. The findings of the study revealed that the model exhibited the capability to anticipate the point of origin of crack initiation.

Zarubin and Zimin [60] analyzed the nonisothermal creep of the exterior of the rocket engine combustion chamber. The application of the power-law model was employed to determine the creep, and an illustration was provided to

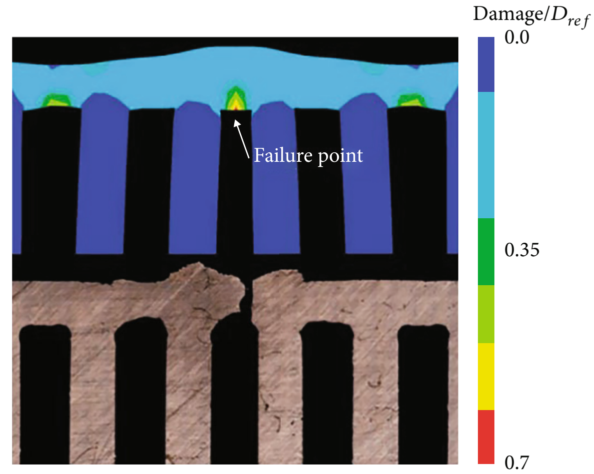


Figure 12: Comparison of cooling channel deformation. Numerical results of deformation and damage distribution (top); photograph of the middle cross section of the TMF panel (bottom) [58].

compute the stress-strain condition of the shell. This allowed for the assessment of the accumulation of the absolute value of the inelastic deformation of the inner wall of the material, which impacts the damage of the shell. The aforementioned study pertains to the investigation of pure creep in a combustion chamber conducted by scholars. Researchers were almost concluding their work on the pure creep of the combustion chamber, so they used the structural relationship of the material and the change in the structure to figure out the creep life, instead of a simple model like Larson-Miller.

3.4. Creep of Other Parts. Mordfin [61] conducted the initial study on the creep of aircraft joints. His article introduced the testing apparatus and testing technology utilized in lap joint creep testing. Then, he conducted high-temperature creep experiments on riveted aluminum alloy and spot-welded stainless steel connections. The test results revealed that the creep of the riveted joints was significantly greater than that of the unriveted sheet, but not so great as to render the sheet's creep insignificant in comparison to that of the joints. Two years later, Mordfin and Legate [62] present the results of 55 creep and creep-rupture experiments on structural joints based on the creep properties of the joint's materials in tension, shear, and bearing. A simple method for predicting the fracture time, fracture mode, and deformation of structural joints in creep under constant load and temperature was described. The active cooling hood lip test-bed components' elastic, elastoplastic, and elastoplastic creep analysis findings were provided by Arya et al. [63] who also forecast the cycle crack start life of the hood lip. Using Barrett and Sherby's [64] and Freed and Verrilli's [65] experimental data, the form of the creep law was determined. In a comparison of predicted cyclic lives, the cyclic life prediction derived from the elastic-plastic-creep analysis was the lowest and, hence, the most accurate. The impact of thermal barrier coating on the damage behavior of the hot gas wall of copper alloy was investigated by Fassin et al. [66]. The application of thermal barrier coating (TBC)

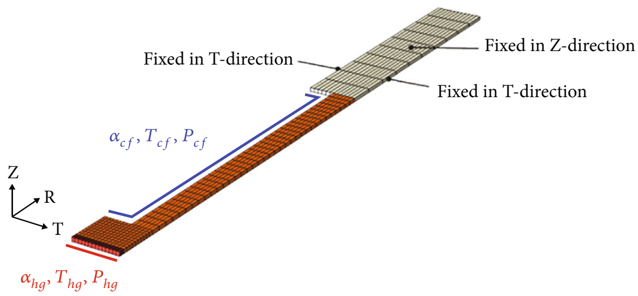


Figure 13: Finite element model of the cooling channel segment with TBC with thermal and static boundary conditions [66].

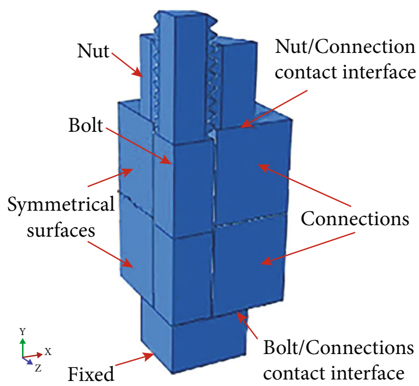


Figure 14: Finite element model of threaded connection [70].

resulted in a decrease of approximately 200 Kelvin in the hot wall temperature. Simultaneously, the author employed the anisotropic damage model [67] which was self-developed, to examine the force exerted on the structural wall of a rocket engine nozzle. The author also conducted a comparison of the damage distribution and deformation behavior of the hot wall with and without a hot runner. The findings suggest that the utilization of thermal barrier coating yielded a favorable impact on the damage behavior and deformation of the heated wall. Figure 13 displays a finite element model of a cooling channel segment equipped with a thermal barrier coating, subject to both thermal and static boundary conditions.

The skin creep of hypersonic vehicles during flight was investigated by Clough et al. [68]. The study involved simulating the significant creep deformation resulting from the heat load experienced by the typical area plate during repeated high-speed flight. This was achieved through the utilization of the small strain plastic method and the previous constitutive relationship [69]. The findings indicate that the creep strain expanded to approximately 98% of the thermal strains induced during two representative flight cycles. The comprehensive findings indicate that the creep mechanism is operational in mitigating stress by augmenting inelastic strain. Honglei [70] conducted a study on the high-temperature creep behavior of threaded connection pairs in aeroengines. The Kachanov-Robotnov creep damage model was employed to estimate the creep damage of bolts. The obtained results exhibited a high level of concurrence with the administered test. Figure 14 depicts the finite element model of the threaded connection.

Table 1: Methods commonly used in the above literature.

	Method	Literatures
1	Miner	[23], [31], and [32]
2	Larson-Miller	[29], [31], [32], [34], [49], and [50]
3	Lagrange-Bhat	[25]
4	Robinson	[29]
5	BP network	[36]
6	Skeleton point stress method	[38]
7	Theoretical-experimental	[48]
8	DCTKS	[41]
9	Norton	[42], [56]
10	Cross-scale modeling method	[42]
11	Viscoplastic model	[54]
12	Chaboche	[58]
13	Lemaitre	[58]
14	Power-law	[57]
15	Kachanov-Robotnov	[70]
16	ESF	[71]

Table 2: Calculation object classification.

Calculation object	Literatures
Creep life calculation by constitutive equation	[56], [58], [60], and [70]
Creep life calculation	[29], [31], [32], [34], [36], [38], [48], [49], and [71]
Creep-fatigue life	[23], [25], [39], [50], [41], [42], [46], [47] and [54]

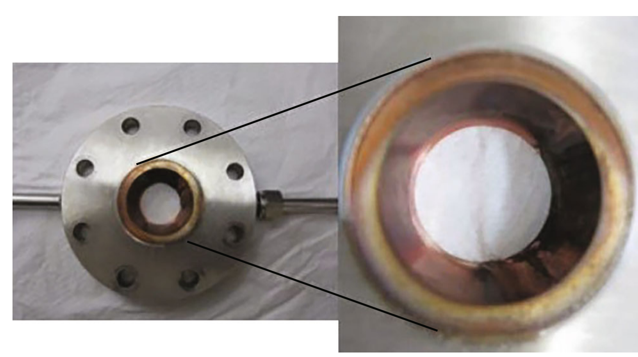
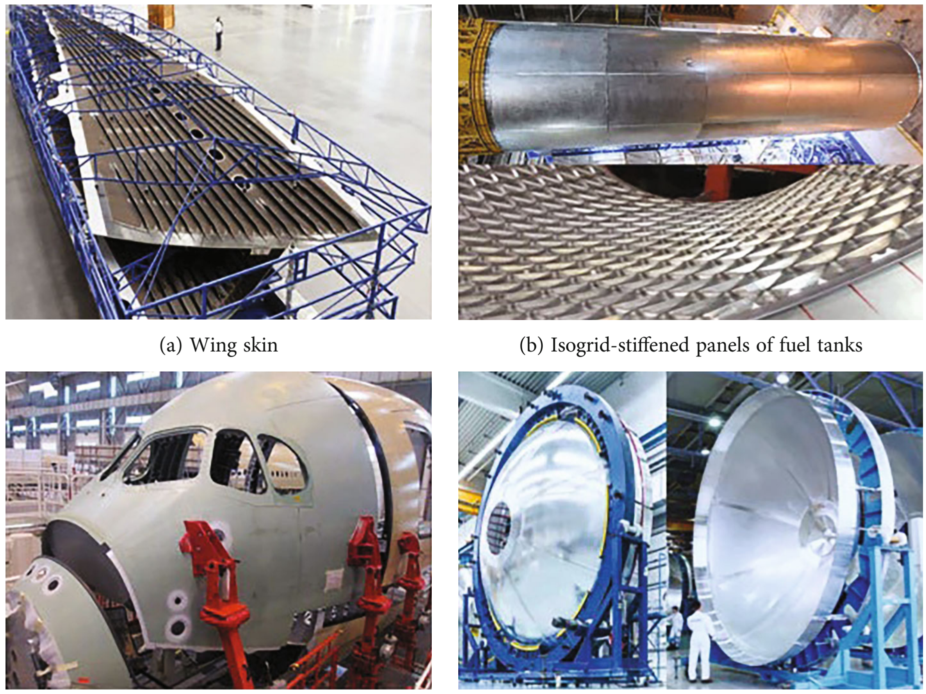


Figure 15: Appearance of TBC sample after cyclic heating test [74].

Ferraiuolo [71], in conjunction with the effective stress function algorithm [72], conducted a finite element thermal structure analysis taking plasticity and creep into consideration. It was demonstrated that the effective stress function algorithm was appropriate for thrust chamber analysis and could produce accurate results in a reasonable amount of time.

This paper summarizes the methods commonly employed in the aforementioned literature, as displayed in Table 1. Table 2 displays the classification of calculation objects according to Section 2 of this paper.



(a) Wing skin

(b) Isogrid-stiffened panels of fuel tanks

(c) Nose panels

(d) Bulkhead panels

FIGURE 16: Current and potential application of creep age forming in aircraft and launch vehicles [80].

By summarizing the aforementioned research, it is evident that within the aerospace field, certain classical models were utilized to compute creep in the literature several years ago, with the Larson-Miller equation being the most commonly employed. Over time, there has been a rapid development in the fields of computer science and finite element. An increasing number of academics are utilizing damage mechanics to introduce constitutive equations and damage variables in order to predict the failure time and fracture strain of high-temperature structures. In contemporary times, academics have put forth numerous novel approaches for forecasting creep that deviate from conventional models. Kaishang et al. have successfully implemented the cross-scale modeling approach to evaluate creep-fatigue damage and predict the lifespan of noncontinuous structures. Numerous instances exist wherein the computation of the interaction life between creep and fatigue is performed. In recent times, there has been a rise in instances of utilizing the constitutive equation to determine the creep life. However, such occurrences remain relatively scarce. In the future, there may be a heightened emphasis on researching novel constitutive relations that are appropriate for implementation in aircraft.

4. Improvement Measures of Creep

In the prior work, the creep phenomena in aircraft were summarized. The manifestation of creep in aircraft components is known to cause irreversible damage, resulting in component deformation and decreased service efficiency. Furthermore, this phenomenon poses a safety risk during flight operations. Thus, it is imperative to implement efficient strategies to mitigate creep.

Asraff et al. [73] conducted a study to evaluate the high-temperature creep characteristics of four distinct copper alloys. The study's findings indicate that the Cu-Cr-Zr-Ti alloy possesses superior properties compared to other alloys. Appearance of TBC sample after cyclic heating test is demonstrated in Figure 15.

This suggests that materials exhibiting favorable creep resistance may be chosen to mitigate component creep. According to Osigwe et al. [49], the utilization of hydrogen fuel in an engine resulted in a higher creep life compared to natural gas. This suggests that the creep life can be enhanced by altering the fuel type utilized. Kimura et al. [74] employed a two-dimensional finite element simulation technique to evaluate the creep damage and low-cycle fatigue damage of the wall of the combustion chamber. Appearance of TBC sample after cyclic heating test is demonstrated in Figure 15. In these simulations, the effects of various heat treatment techniques on the durability of the lining material, the thermal barrier coating insulation layer, and the thermal expansion of the shell were investigated. The study revealed that the thermal barrier coating exhibits the most significant impact on extending the operational lifespan. However, the extent of its influence is contingent upon the physical characteristics of the lining material. The implementation of thermal barrier coating has the potential to mitigate the temperature of components, thereby diminishing the likelihood of creep. Thus, the primary purpose of all measures for thermal protection is to decrease creep.

Figure 17: The world's largest commercial aircraft A380 wing panel [81].

5. Benefits of Creep

In the aerospace field, the phenomenon of creep can serve a dual purpose, whereby it can be detrimental in certain cases, while in others, it can aid in the completion of the formation of aircraft components. Creep aging forming is a method of forming that utilizes the creep property of gradual plastic deformation of metal materials at a specific temperature and pressure for an extended period of time to synchronize forming and aging strengthening [75]. After heat treatment, the metal components are affixed to the tooling surface of the die by mechanical loading or vacuum loading. The whole assembly is then placed in the heat treatment equipment, the predetermined time and temperature are set in the equipment, and the elastic deformation is gradually transformed into plastic deformation [76]. Current and potential application of creep age forming in aircraft and launch vehicles is shown in Figure 16. In comparison to conventional metal plastic forming techniques, creep aging forming exhibits numerous advantages. The implementation of this technique has been shown to significantly decrease the likelihood of machining cracks, enhance the microstructural and mechanical characteristics of materials, and exhibit a high degree of repeatability. The formed parts exhibit high forming accuracy, and the majority of residual stresses in the components have been removed [77]. The Textron Company of the United States utilized creep aging to form the composite curved upper wing skin of the upper and lower skin panels of the B-1B bomber, while the orthogonal grid structural components of the Hercules IV rocket were also formed using the same method [78]. The upper wing wall panel of the B-1B bomber possessed a dimension of $2.74\,\mathrm{m} \times 15.25$ m, with a thickness variation range of 2.54~63.5 mm. The wall panel's maximum fitting error was limited to 0.25 mm. Airbus had manufactured A380 wing sheet skin using creep aging, with a length of 33 meters and a fit of less than 0.25 millimeters [79]. This equipment holds the distinction of being the biggest hot pressing tank globally, as demonstrated in Figure 17.

6. Conclusion

During flight, the aircraft is exposed to high-temperature and high-pressure conditions in its surrounding environment. As a result, the uppermost parts of the aircraft may experience creep, leading to structural changes that can compromise the safety of the flight and potentially result in catastrophic accidents. The present study provides an overview of the conventional models for creep calculations, as well as the creep behavior and corresponding calculation models for various components of aircraft engines, such as turbine blades, turbine disks, and combustion chambers. Several classical models were utilized in previous studies to compute creep, with the Larson-Miller equation being the most commonly observed. These models were relatively straightforward in nature. As time passed, there has been a rapid development in the fields of computer science and finite element. By using constitutive equations and damage variables based on damage mechanics, more and more researchers are able to forecast the failure time and fracture strain of high-temperature structures. The Kachanov-Robotnov constitutive equation is a frequently utilized model in the field. In recent years, academics have proposed numerous novel approaches for forecasting creep that diverge from conventional models. Furthermore, a summary of the effective measures to reduce creep is presented, including the selection of creep-resistant materials, the use of hydrogen fuel, the application of thermal barrier coating, and other thermal protection measures. Finally, it is proposed that creep is not only harmful in the aerospace industry but can also be used to complete the forming of aircraft parts, a process known as creep aging forming.

This paper provides an overview of the research conducted over the past century and the most recent advancements in creep research. Potential areas for future study include conducting creep analysis on additional aircraft components, developing creep models that are appropriate for diverse components, and exploring novel strategies for mitigating creep.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] J. Betten, *Creep Mechanics*, Springer, Berlin, Heidelberg, 2022.

[2] R. E. Dundas, D. A. Sullivan, and F. Abegg, "Performance monitoring of gas turbines for failure prevention," in *Turbo Expo: Power for Land, Sea, and Air. American Society of Mechanical Engineers*, vol. 78965, article V004T10A013, American Society of Mechanical Engineers, 1992.

[3] C. G. Skamniotis and A. Cocks, "2D and 3D thermoelastic phenomena in double wall transpiration cooling systems for gas turbine blades and hypersonic flight," *Aerospace Science and Technology*, vol. 113, article 106610, 2021.

[4] F. Hötte, T. Fiedler, M. C. Haupt, P. Lungu, C. V. Sethe, and O. J. Haidn, "Experimental investigations of thermomechanical fluid–structure interaction in rocket combustion chambers," *Journal of Propulsion and Power*, vol. 35, no. 5, pp. 906–916, 2019.

[5] F. Hötte, C. V. Sethe, T. Fiedler, M. C. Haupt, O. J. Haidn, and M. Rohdenburg, "Experimental lifetime study of regeneratively cooled rocket chamber walls," *International Journal of Fatigue*, vol. 138, article 105649, 2020.

[6] M. Xiaying, *Creep Mechanics*, Xi'an Jiaotong University, Xi'an, 1990.

[7] W. C. Engelund, S. D. Holland, C. E. Cockrell Jr., and R. D. Bittner, *Propulsion System Airframe Integration Issues and Aerodynamic Database Development for the Hyper-X Flight Research Vehicle*, 1999.

[8] K. R. Athul, U. T. S. Pillai, A. Srinivasan, and B. C. Pai, "A review of different creep mechanisms in Mg alloys based on stress exponent and activation energy," *Advanced Engineering Materials*, vol. 18, no. 5, pp. 770–794, 2016.

[9] W. Blum, P. Eisenlohr, and F. Breutinger, "Understanding creep–a review," *Metallurgical and Materials Transactions A*, vol. 33, no. 2, pp. 291–303, 2002.

[10] O. D. Sherby and P. M. Burke, "Mechanical behavior of crystalline solids at elevated temperature," *Progress in Materials Science*, vol. 13, pp. 323–390, 1968.

[11] T. Xuefeng, S. Duoqi, X. Yang, and S. Yantao, "Creep property of aerogel insulation composite material and its influence on thermal protection structure," in *Proceedings of the 19th national conference on composite materials*, pp. 1–10, Xi'an,-China, 2016.

[12] L. M. Kachanov, "On the creep fracture time," *Izvestia Academii Nauk Sssr Otdelenie Tekhnicheskich Nauk*, vol. 8, pp. 26–31, 1958.

[13] H. Kunaciskał and J. J. Skrzypek, "CDM based modelling of damage and fracture mechanisms in concrete under tension and compression," *Engineering Fracture Mechanics*, vol. 71, no. 4-6, pp. 681–698, 2004.

[14] B. Z. Wang, Q. Fu, and H. F. Yu, "A creep model of nickel based single crystal superalloy at high temperature based on rafting mechanism," *Journal of Aerospace Power*, vol. 2016, pp. 26–31, 2016.

[15] J. Lemaitre, "A continuous damage mechanics model for ductile fracture," *Journal of Engineering Materials and Technology*, vol. 107, no. 1, pp. 83–89, 1985.

[16] F. Wang and W. Guo, "Continuum damage mechanics analysis of high temperature creep and creep fracture for titanium alloy IMI834," *Journal of Mechanical Strength*, vol. 27, no. 4, pp. 530–533, 2005.

[17] R. C. Yang, H. Wang, H. T. Yang, K. Chen, and X. B. Yuan, *Aging Behavior Descriptions for Main Steam Pipe Steels 12Cr1MoV and 15CrMo by Larson-Miller Parameter*, Material Science and Technology, 2002.

[18] Z. Peidao, "Failure and lesson of aeroengine turbine rotor blade," *Journal of Materials Engineering*, vol. 2003, pp. 30–33, 2003.

[19] R. H. Priest and E. G. Ellison, "A combined deformation map-ductility exhaustion approach to creep-fatigue analysis," *Materials Science and Engineering*, vol. 49, no. 1, pp. 7–17, 1981.

[20] Y. Takahashi, "Study on creep-fatigue evaluation procedures for high-chromium steels–part I: test results and life prediction based on measured stress relaxation," *International Journal of Pressure Vessels & Piping*, vol. 85, no. 6, pp. 406–422, 2008.

[21] E. L. Robinson, "Effect of temperature variation on the long-time rupture strength of steels," *Transactions of the American Society of Mechanical Engineers*, vol. 74, no. 5, pp. 777–780, 1952.

[22] M. U. Yuanwei and L. U. Shan, "Reliability prediction on creep rupture and LCF life for a turbine disk," *Gas Turbine Experiment and Research*, vol. 28, no. 3, p. 13, 2015.

[23] S. Majumdar, "Low-cycle fatigue and creep analysis of gas turbine engine components," *Journal of Aircraft*, vol. 12, no. 4, pp. 376–382, 1975.

[24] L. F. Coffin Jr., "A study of the effects of cyclic thermal stresses on a ductile metal," *Transactions of the American Society of Mechanical Engineers*, vol. 76, no. 6, pp. 931–949, 1954.

[25] M. H. Sabour, *Creep-Fatigue Interaction in Aircraft Gas Turbine Components by Simulation and Testing at Scaled Temperatures*, Doctoral dissertation, Concordia University, 2005.

[26] R. B. Bhat, "Lagrange-Bhat method to analyze vibration of structures using boundary characteristic orthogonal polynomials," in *International Conference on Current Advances on Mechanical Design and Production, MDP-8*, Cairo, Egypt, 2004.

[27] B. S. Karpinos, V. V. Samuleev, B. A. Lyashenko, E. V. Lais'ke, and A. V. Rutkovs'kyi, "Thermal cyclic creep and long-term strength of the material of aircraft gas turbine blades after operation," *Strength of Materials*, vol. 45, no. 5, pp. 542–548, 2013.

[28] A. N. Vetrov and A. G. Kucher, "Estimate of remaining life of blades in aircraft gas turbines from accumulated creep strain," *Strength of Materials*, vol. 25, no. 1, pp. 42–47, 1993.

[29] G. Marahleh, A. R. I. Kheder, and H. F. Hamad, "Creep-life prediction of service-exposed turbine blades," *Materials Science*, vol. 42, no. 4, pp. 476–481, 2006.

[30] R. V. Hart, "Assessment of remaining creep life using accelerated stress-rupture tests," *Metals Technology*, vol. 3, no. 1, pp. 1–7, 1976.

[31] M. Naeem, "Implications of day temperature variation for an aero-engine's HP turbine- blade's creep life-consumption," *Aerospace Science and Technology*, vol. 13, no. 1, pp. 27–35, 2009.

[32] M. Naeem and I. Ul-Haq, "Implications of a military turbofan's high-pressure turbine erosion for blade's creep life-consumption," *Journal of Propulsion and Power*, vol. 26, no. 1, pp. 177–182, 2010.

[33] N. Ejaz, I. N. Qureshi, and S. A. Rizvi, "Creep failure of low pressure turbine blade of an aircraft engine," *Engineering Failure Analysis*, vol. 18, no. 6, pp. 1407–1414, 2011.

[34] S. Jianzhong and Z. Hongfu, "Impacts of operating and health conditions on civil aircraft engine turbine blade creep life," *China Mechanical Engineering*, vol. 25, no. 11, p. 1511, 2014.

[35] M. R. Jahangiri and M. Abedini, "Effect of long time service exposure on microstructure and mechanical properties of gas turbine vanes made of IN939 alloy," *Materials & Design*, vol. 64, no. 10, pp. 588–600, 2014.

[36] A. Sixu, *Research on Prediction for Creep Life of the Blades in Aero Engine Based on Creep Properties and Microstructure*, Northeastern University, 2015.

[37] B. Sahoo, S. K. Panigrahi, and R. K. Satpathy, "Creep life degradation and microstructure degeneration in a low-pressure turbine blade of a military aircraft engine," *Journal of Failure Analysis & Prevention*, vol. 17, no. 3, pp. 529–538, 2017.

[38] Z. Li, Z. Wen, H. Pei et al., "Creep life prediction for a nickel-based single crystal turbine blade," *Mechanics of Advanced Materials and Structures*, vol. 29, no. 27, pp. 6039–6052, 2022.

[39] H. Mao, S. Mahadevan, and G. Dan, "Probabilistic creep-fatigue life prediction of aircraft engine blades," in *15th ASEE Engineering Mechanics Conference*, Türkiye, Istanbul, 2002.

[40] P. Paris and F. Erdogan, "A critical analysis of crack propagation laws," *Transaction of the ASME. Series D, Journal of basic engineering*, vol. 85, no. 4, pp. 528–533, 1963.

[41] L. K. Song, G. C. Bai, and C. W. Fei, "Dynamic surrogate modeling approach for probabilistic creep-fatigue life evaluation of turbine disks," *Aerospace Science and Technology*, vol. 95, p. 105439, 2019.

[42] V. Shlyannikov, I. Ishtyryakov, and A. Tumanov, "Characterization of the nonlinear fracture resistance parameters for an aviation GTE turbine disc," *Fatigue and Fracture of Engineering Materials and Structures*, vol. 43, no. 8, pp. 1686–1702, 2020.

[43] V. N. Shlyannikov and A. V. Tumanov, "Characterization of crack tip stress fields in test specimens using mode mixity parameters," *International Journal of Fracture*, vol. 185, no. 1-2, pp. 49–76, 2014.

[44] W. Runzi, *A Creep-Fatigue Life Prediction Model Based on Strain Energy Density Exhaustion Criterion and Its Application on Aero-Engine Turbines Discs*, East China University of Science and Technology, 2019.

[45] Y. Takahashi, "Effect of cyclic loading on subsequent creep behaviour and its implications in creep-fatigue life assessment," *Materials at high temperatures*, vol. 32, no. 5, pp. 492–501, 2015.

[46] V. Shlyannikov, A. Sulamanidze, and R. Yarullin, "Fatigue and creep-fatigue crack growth in aviation turbine disk simulation models under variable amplitude loading," *Engineering Failure Analysis*, vol. 131, article 105886, 2022.

[47] L. Kaishang, W. Runzi, Z. Xiancheng, and T. Shangdong, "Creep-fatigue life prediction based on multi-scale modelling approach," *Pressure Vessel Technology*, vol. 38, no. 11, p. 9, 2021.

[48] V. V. Pokrovskii, V. G. Sidyachenko, V. N. Ezhov, and S. B. Kulishov, "Theoretical-experimental model for predicting crack growth rate in structural alloys under combined action of fatigue and creep," *Strength of Materials*, vol. 41, no. 1, pp. 81–87, 2009.

[49] E. O. Osigwe, A. Gadbriggs, and T. Nikolaidis, "Thermodynamic performance and creep life assessment comparing hydrogen- and jet-fueled turbofan aero engine," *Applied Sciences*, vol. 11, no. 9, p. 3873, 2021.

[50] K. M. Tomevenya and S. J. Liu, "Probabilistic fatigue-creep life reliability assessment of aircraft turbine disk," *Journal of Mechanical Science and Technology*, vol. 32, no. 11, pp. 5127–5132, 2018.

[51] R. J. Quentmeyer, "Experimental fatigue life investigation of cylindrical thrust chambers," in *Presented at the AIAA Thirteenth Propulsion Conference*, Orlando, FL, 1977.

[52] R. S. Jankovsky, V. K. Arya, J. M. Kazaroff, and G. R. Halford, *Structurally Compliant Rocket Engine Combustion Chamber: Experimental and Analytical Validation*, National Aeronautics and Space Administration, Office of Management, Scientific and Technical Information Program, 1994.

[53] H. J. Kasper, *Thrust Chamber Life Prediction*, NASA. Marshall Space Flight Center Advan. High Pressure O2 (H2 Technol, 1984.

[54] I. K. Sung, B. Northcutt, K. Rubel, and W. Anderson, "A subscale-based life prediction methodology for rocket engine combustor," in *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Huntsville, Alabama, 2003.

[55] D. N. Robinson and S. M. Arnold, "Effects of state recovery on creep buckling under variable loading," *Journal of Applied Mechanics*, vol. 57, no. 2, pp. 313–320, 1990.

[56] P. Jaihyun, *Comparison of Creep Properties and Failure Analysis for Heat Resistance Cast Steels*, 2013.

[57] V. S. Zarubin, V. N. Zimin, and G. N. Kuvyrkin, "Estimation of the combustion chamber shell working capacity for the reusable liquid-propellant rocket engine," *Russian Aeronautics (Iz VUZ)*, vol. 61, no. 3, pp. 425–433, 2018.

[58] T. Masuoka and J. R. Riccius, "Life evaluation of a combustion chamber by thermomechanical fatigue panel tests based on a creep fatigue and ductile damage model," *International Journal of Damage Mechanics*, vol. 29, no. 3, article 105678951983588, 2019.

[59] J. L. Chaboche, "Constitutive equations for cyclic plasticity and cyclic viscoplasticity," *International Journal of Plasticity*, vol. 5, no. 3, pp. 247–302, 1989.

[60] V. S. Zarubin and V. N. Zimin, "On the cyclic deformation of the shell of the combustion chamber of a multiple-action liquid-propellant rocket engine," *Mechanics of Solids*, vol. 57, no. 1, pp. 132–138, 2022.

[61] L. Mordfin, *Creep and Creep-Rupture Characteristics of Some Riveted and Spot-Welded Lap Joints of Aircraft Materials*, Technical report archive & image library, 1954.

[62] L. Mordfin and A. C. Legate, *Creep Behavior of Structural Joints of Aircraft Materials under Constant Loads and Temperatures*, 1957.

[63] V. K. Arya, M. E. Melis, and G. R. Halford, "Finite element elastic-plastic-creep and cyclic life analysis of a cowl lip," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 14, no. 10, pp. 967–977, 1991.

[64] C. R. Barrett and O. D. Sherby, "Steady-state creep characteristics of polycrystalline copper in the temperature range of 480 'C to 950 'C," *Transactions of the Metallurgical Society of AIME*, vol. 230, pp. 1322–1327, 1964.

[65] A. D. Freed and M. J. Verrilli, *A Viscoplastic Theory Applied to Copper*, 1988, NASA TM-100831.

[66] M. Fassin, S. Wulfinghoff, and S. Reese, "Modelling of thermal barrier coatings and their influence on the lifetime of rocket engine nozzle structures," *VII European Congress on Computational Methods in Applied Sciences and Engineering*, 2016.

[67] M. Fassin, S. Wulfinghoff, and S. Reese, "Different numerical time integration schemes for elastoplasticity coupled to anisotropic damage," *Applied Mechanics and Materials*, vol. 784, pp. 217–224, 2015.

[68] J. L. Clough, A. A. Oberai, and J. A. Camberos, "Deformation of a panel in repeated high speed flow modeled with creep and multiplicatively-decomposed plasticity," in *23rd AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Montreal, Quebec, Canada, 2020.

[69] Z. Li, M. O. Bloomfield, and A. A. Oberai, "Simulation of finite-strain inelastic phenomena governed by creep and plasticity," *Computational Mechanics*, vol. 62, no. 3, pp. 323–345, 2018.

[70] Z. Honglei, *Study on High Temperature Creep and Fatigue Life for Typically Threaded Connections of Aero-Engine*, Northwestern Polytechnical University, 2016.

[71] M. Ferraiuolo, "Investigating the effective stress function algorithm for the thermostructural analysis and design of liquid rocket engines thrust chambers," *Journal of Thermal Stresses*, vol. 44, no. 12, pp. 1389–1406, 2021.

[72] M. Kojic, "Stress integration procedures for inelastic material models within the finite element method," *Applied Mechanics Reviews*, vol. 55, no. 4, pp. 389–414, 2002.

[73] A. K. Asraff, R. Aparna, D. Kumaresan, and R. Muthukumar, "Comparison of creep properties of four copper alloys and creep based stress analysis of a rocket engine combustion chamber," *Procedia Engineering*, vol. 55, pp. 45–50, 2013.

[74] T. Kimura, S. Moriya, and M. Takahashi, "Effects of heat treatments to inner liner material, thermal barrier coating, and outer shell material on lifetime of a combustion chamber," *Acta Astronautica*, vol. 158, pp. 244–252, 2019.

[75] D. M. Harnbrick, "Age forming technology expanded in an autoclave," *SAE Transactions*, vol. 4, no. 6, pp. 649–664, 1986.

[76] L. Wenbo, X. Ran, Z. Shan, and L. Lili, "Application of sheet metal forming teachnology in aviation and aerospace," *Aerospace Manufacturing Technology*, vol. 1, p. 5, 2022.

[77] M. Sallah, J. Peddieson, and S. Foroudastan, "A mathematical model of autoclave age forming," *Journal of Materials Processing Technology*, vol. 28, no. 1-2, pp. 211–219, 1991.

[78] H. Li and M. Fu, "Deformation based processing of materials:-behavior, performance, modeling, and control," *Journal of Plasticity Engineering*, vol. 26, no. 4, p. 84, 2019.

[79] Z. Lihua, L. Jianguo, and T. A. Dean, "A review of the development of creep age forming: experimentation, modelling and applications," *International Journal of Machine Tools and Manufacture*, vol. 51, no. 1, pp. 1–17, 2011.

[80] Y. Li, *Experimental Investigation and Numerical Simulation of Creep Age Forming with Aluminium-Copper-Lithium Alloy 2050*, 2017.

[81] K. Watcham, "Airbus A380 takes creep age-forming to new heights," *Materials World*, vol. 12, no. 2, pp. 10-11, 2004.