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Literature Review of Fatigue Life Performance of Ceramic Materials

Georgios KARADIMAS and Konstantinos SALONITIS
School of Aerospace, Transport, and Manufacturing, Cranfield University, Cranfield MK43 0AL, UK.

Abstract. Ceramic materials are widely used nowadays in the aerospace sector. However, functional ceramics have not yet been fully researched in terms of their life expectancy under all possible loading scenarios. Ceramics have low toughness and high brittleness, but great thermal properties as it has been widely documented in the literature. A lack of research however with regards to ceramic material life expectancy models is evident. The fatigue life of ceramic materials is not thoroughly researched and there is a need for comparing them with more traditional materials used for similar purpose applications. In the present paper, the fatigue performance of several ceramic materials will be analyzed by using S-N curves, simulating the cumulative damage caused to these materials by different constant amplitude stresses applied from a wide range of applications and more specifically, aero-engine applications. Finally, the already existing literature on ceramic failure mechanisms and models will be evaluated and compared with the simulated life expectancy models to identify improvement opportunities and a guide for developing and deploying these materials to the extended use of applications.

Keywords. Fatigue Life, Ceramics, CMCs, Life Expectancy.

1. Introduction

Fatigue creates progressive damage in materials because of cyclic loading. More specifically, fatigue causes crack propagation and material deformation, leading to catastrophic failure of the material [1]. The failure happens due to the cyclic nature of the load that causes the microscopic material imperfections to expand to a microscopic crack and continue to grow when the stress intensity factor of the crack exceeds the fracture toughness of the material, creating rapid propagation or complete fracture of the component [2]. Fatigue fracture has three development stages, crack initiation, crack propagation, and final rupture. These stages are used to calculate high and low cycle fatigue, by implementing the crack initiation, crack propagation, and ultimate failure process steps [3].

Material degradation is caused by the interaction with the environment. For ceramic materials, environmental factors are the main issue for degradation. More specifically, these environmental factors include temperature, external loads, vibrations, etc. To increase the lifespan of ceramics, control of the surrounding environment that ceramic materials are exposed to is required, including the operational load, and altering the composite design. Furthermore, to achieve a greater life span, a life prediction methodology for high-temperature ceramics needs to be developed, including a thorough investigation of the interaction between time-cycle-dependant damage mechanisms.

These damage mechanisms are the ones that limit the life of ceramic materials under dynamic loads.

This paper contributes to the understanding of failure mechanisms and their applications in ceramic materials. Furthermore, the selection of exemplar ceramic materials will be presented in terms of their flexural strength, fracture toughness, tensile strength, and fatigue strength, which include basic criteria for measuring the fatigue life of a composite. The results of the simulation process will be plotted and demonstrated with S-N curves comparing the outcome of the results with other already existing materials in a similar type of applications.

2. Fatigue Life Methods

Ceramics are characterized as strong, hard, electrically insulating, and resistant to high-temperature oxidation, as well as wear and corrosion [4]. They are known for their usage in high-temperature applications like machinery, metal processing refractory materials, and thermal barrier coatings. Nevertheless, literature shows that under a long time high-temperature service or under multiple cycles of high-temperature changes, the mechanical and thermal properties of the ceramic materials would decrease [5]. This is known as the thermal fatigue phenomenon.

For the investigation of the thermal fatigue phenomenon, two different theories have been proposed. The first theory, known as *critical stress fracture theory*, is based on the thermal plasticity of ceramic materials: when thermal stress caused by the temperature difference due to unexpected temperature changes is higher than the inherent strength of a ceramic, thermal shock fracture occurs [6, 7]. The second one, known as the *thermal shock damage theory* is based on the fracture mechanics of ceramics: when the strain energy of the thermal stress exceeds the fracture energy needed for crack nucleation and growth, crack propagation occurs, leading to catastrophic damage [8, 9].

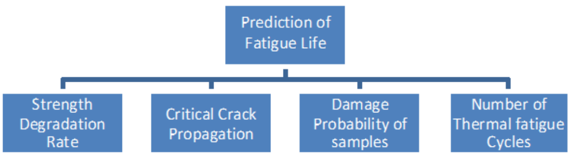

Figure 1. Prediction of fatigue life methods.

For the understanding and accumulation of these two theories, several predictions and testing methods have been created as seen in Figures 1 and 2. Prediction based on the strength degradation rate method has been used to investigate the fatigue behaviour of Al_2O_3, HP-SiN_4, and SiC-based ceramic materials and composites [8]. The outcome of this method is the failure evaluation and the prediction of the thermal fatigue life of a ceramic-based model, which is influenced by stress, load time, and experimental conditions, like the method of damage probability of the sample's method [9, 10]. The critical crack propagation method has been found responsible for finding the duration of time in which a crack reaches the critical length [11]. The prediction method based on the number of thermal fatigue cycles estimates the crack propagation and the length of a crack, which will lead to material failure [12].

Literature indicates that fatigue characterization methods of ceramics are similar to the ones for metals, but in comparison to metals, ceramics are brittle rather than ductile. This is due to the varying testing conditions, testing results, and influencing factors of ceramic materials against metals [13]. The most common characterization method for fatigue in ceramics is based on comparing the mechanical performance of ceramic samples before and after thermal cycles or durations, exposed to high temperatures [5]. This method is separated into three different testing methods as seen in Figure 2 for achieving more reliable results. The strength testing method is a destructive testing procedure that simulates the system and the environment in which a ceramic will be applied [14]. The quenching method is the most used testing method for fatigue life, in which the ceramic material is placed in a high-temperature environment for a period which then is followed by rapid cooling with air, water, and solvent to analyse and measure the fracture morphology of the material [15, 16]. Finally, the acoustic emission testing technique is a physical phenomenon where the transient electric wave is produced by the rapid release of energy from crack formation or plastic deformation, which occurs because of the applied internal or external stress and temperature. Research shows that acoustic emission signal for ceramics is large and distinguishable from noise [17].

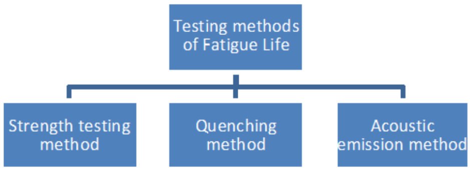

Figure 2. Testing methods of ceramics fatigue life prediction

Further studies show that for composite materials fatigue life can be approached by using fracture mechanics parameters, including the stress intensity factor [18-20]. Moreover, S (stress) -N (number of cycles) curves are used to calculate relatively smaller cracks for fatigue life collectively. This method allows for crack initiation on a large scale of un-notched geometry [21]. S-N curve models are implemented from fatigue damage formulations or obtained empirically or statistically by implementing the Weibull distribution [22, 23]. In continuous, S-N curve models can be used from both monolithic and composite materials, with the fatigue damage growth pattern varying according to the material structure [24]. These curve models can also be used for the fatigue life prediction of material including fatigue damage justification and the stress ratio effect [25].

3. Fatigue Life Expectancy Methods

The selection of the appropriate material for a specific application will provide reduced overall cost, increased life expectancy, and greater safety outcomes. [26-28]. Ceramic materials are known for their high temperature, corrosion, and oxidation resistance, but are also known for their low toughness and strength when high loads are applied. That is why further development has been researched and achieved for ceramic materials by reinforcing them with different kinds of fibres and substrates, enhancing their toughness, strength, and hardness [29, 44].

In terms of the life expectancy of a material, the shear stress-strain (shear modulus), fracture toughness, and flexural strength are very important. These mechanical values help select the required ceramic materials to simulate the life expectancy of a component. In addition, these values help calculate the shear stresses and amplitudes of each material under a constant load to estimate the endurance limit of each material until fatigue failure occurs. [30, 31].

Figures 3 and 4 demonstrate a variety of ceramic and ceramic composite materials compared in terms of their flexural strength, fracture toughness, shear modulus, and fatigue strength. This allows for an estimation from which the more capable materials for high-temperature applications can be selected and tested [29].

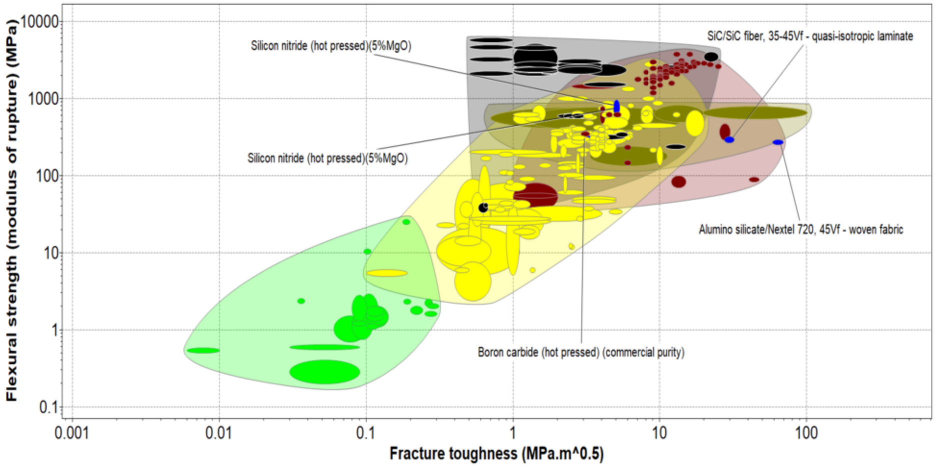

Figure 3. Flexural Strength vs Fracture Toughness comparison of Ceramics.

Figure 3 highlights the flexural strength and fracture toughness of different types of ceramic materials including ceramic composites, fibres, technical ceramics, and ceramic foams, plotted in GRANTA software. Flexural strength indicates the maximum amount of stress a material can withstand before it yields. If the material subjected to stress is homogeneous, the flexural strength is equal to the material's tensile strength [32]. The higher the flexural strength a material offers, the more restoration process steps are required. This means that materials with high flexural strength have longer span restoration periods and require more agile treatment options when a material has a thinner overall thickness (lesser material overall weight) [33]. That is because flexural strength affects the thickness of the restoration walls and due to the high-strength material allows for low wall thickness, equal to when a material has high fracture toughness.

Furthermore, fracture toughness shows the critical stress intensity factor of a crack that occurs to a material, which after some time the applied critical stress becomes rapid and irreplaceable. Thickness affects crack propagation [36]. Thin components have plain stress conditions, and thick components have plain strain conditions, which offer the lowest fracture toughness values [37]. Ceramic materials have lower fracture toughness than metals but greatly improve the stress fracture, which is validated as 1.5 orders of magnitude strength increase, relative to metals [38]. As can be observed in Figure 3, ceramic matrix composites have the best overall performance in terms of flexural strength and fracture toughness, although some ceramic fibres have higher flexural strength but very low fracture toughness [39].

Figure 4 compares the tensile strength and fatigue strength of the different categories of ceramic materials which are plotted in GRANTA software. Tensile strength indicates the mechanical performance of a material. Ceramics show compressive strengths ten times higher than their tensile strength, meaning that their overall tensile strength is much lower than other metals or aluminum alloys. This is because ceramics have flaws in their microstructure, and internal or surface cracks [40].

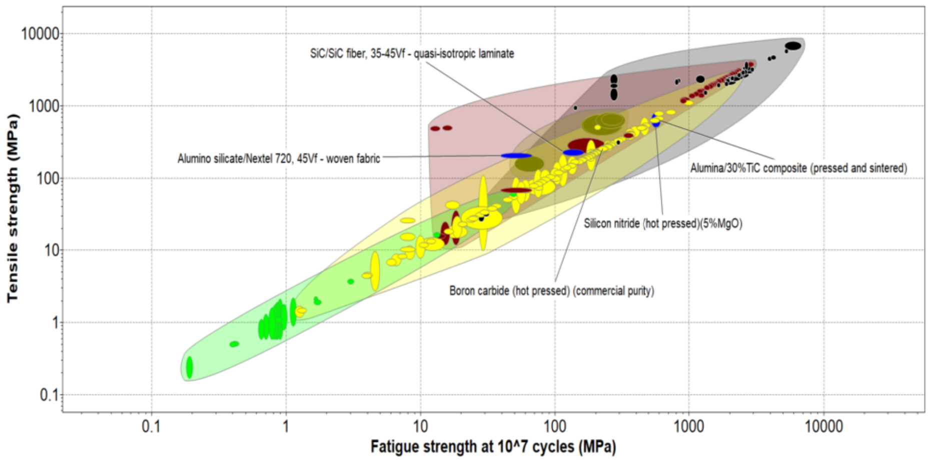

Figure 4. Tensile Strength vs Fatigue Strength comparison of Ceramics.

Fatigue strength is the highest stress applied to a material for a specific number of cycles without breaking. Certain attributes might cause the fatigue strength of a material to be lower. These conditions are affected by environmental factors, such as corrosion [41]. Furthermore, there are different types of fatigue strength, such as mechanical, creep, thermal, thermo-mechanical, fretting, and corrosion fatigue. However, fatigue strength is mostly defined as mechanical fatigue, the stress percentage applied without causing catastrophic failure to the material. Until now it has been very hard to calculate ceramic material fatigue behaviour including the fatigue life and fatigue crack growth rate due to having scatter, up to six orders of magnitude [42].

Based on figures 3 and 4, four technical ceramic-based materials were chosen, (highlighted in blue colour). The selection criteria for these materials were: high values of flexural strength, fracture toughness, tensile, and fatigue strength. Such performance in addition to the microstructure of the materials would allow for a comparative case study with other high-temperature ceramic application materials with the expectation to offer a better overall fatigue value outcome. Finally, the selected ceramic materials have a similar ceramic base structure to the ceramic materials used in high-temperature applications but have different filler and base material composition values.

Table 1. Selected Ceramics, according to their mechanical values from Figures 3 and 4.

Material Composition	Flexural Strength (MPa)	Fracture Toughness ($MPa.m^{0.5}$)	Tensile Strength (MPa)	Fatigue Strength at 10^7 cycles (MPa)
Al_2O_3(93.25%)/SiO_2(6.75%)	271.5	64	208.5	52.8
SiC(55-65%)/SiC (35-45%)	296.5	29.9	228.5	138
Si_3N_4/5%MgO	792.5	5.05	660.5	565.5
Al_2O_3(30%)/TiC	760	4	633.5	555

Table 1 data allow for the creation of four fatigue life case studies in which the amplitude stress and the number of cycles for each material will be presented with the plot of S-N curve models. These material properties from Table 1 were collected from the GRANTA software material database to allow the creation of the S-N curve diagrams below [35]. The steps leading to the outcome of the S-N curve models were as follow:

- Material selection
- Calculation of strength at 10^3 cycles (S_m) and uncorrected endurance limit ($S_{e'}$)
- Calculation of correction factors
- Calculation of endurance strength (S_e)
- S-N diagram drawing

The design product, which these material models were tested, was a square beam shaft. For the calculation of the previously enlisted parameters and the plot of the S-N diagrams the operating temperature (T=1200^{O}C), the weight of the shaft (W=675lb), diameter (d=0.5inch), type of loading (Bending), and correction factors (loading due to bending (C_L=1), diameter size due to d=0.5inch (C_S=0.93), surface finish with Ra=125 microns as machined (C_F), and assumed reliability of 0.5 (C_r=1)) were used by following similar conditions of previously used in high-temperature ceramic material case studies.

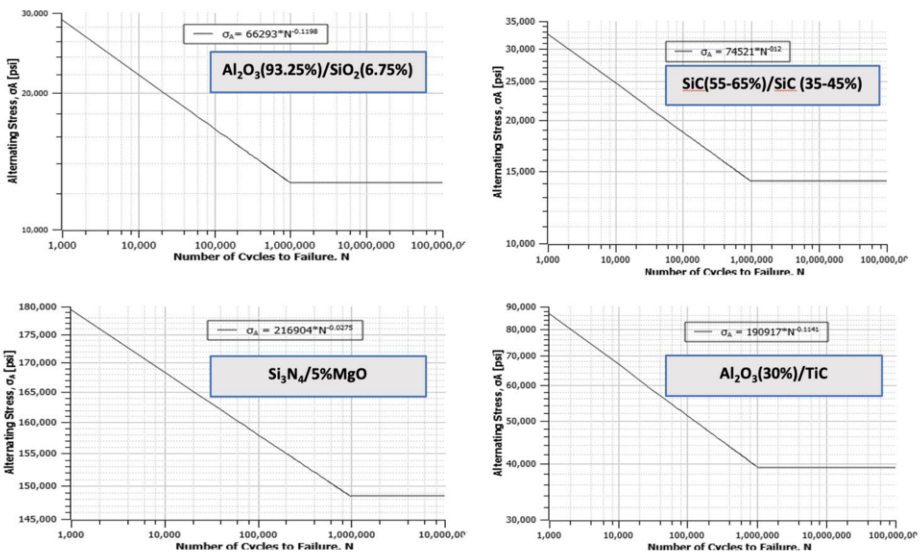

Figure 5. Alternating Stress vs Number of Cycles to failure of four different ceramic composite materials

Figure 5 showcases the alternating stress (σ_A) against the number of cycles to failure of four technical ceramic and ceramic matrix composite materials. For these four case studies, the maximum alternating stress for each one of the four materials was calculated and plotted for a similar amount of several cycles, which was equal to 10^7 cycles. In addition, the alternating stress was calculated by assuming that the components were exposed to bending loading which caused cyclic fatigue to occur.

Furthermore, it can be observed from Figure 5 that Si3N4/5%MgO has the highest alternating stress value (σ_A) and the highest endurance limit in comparison with the other three ceramic materials. This means that this material can withstand for a longer period higher stresses for the same load without failing, leading to greater efficiency results. It must be noted that if the size standard of the specimen increases, then the endurance limit of the material and the alternating stress will decrease. The second material with the highest values was Al_2O_3(30%)/TiC having almost a double alternating stress and endurance limit in comparison with Al_2O_3(93.25%)/SiO_2(6.75%) and SiC (55-65%)/SiC (35-45%). These results lead to the observation that materials with higher ultimate tensile strength (S_{ut}) will lead to a better stress performance outcome.

4. Conclusion

Ceramic materials Fatigue life prediction mechanisms are relying on various measuring methods. Until now four prediction methods investigate the crack growth and damage of ceramic applications. These methods include the strength degradation rate technique, the critical crack propagation method, the damage probability of ceramic samples, and the number of thermal fatigue cycles. In continuous, after a life prediction method has been implemented the next step is the investigation and testing of the fatigue life of the material. Ceramics due to their brittle nature differ from other metal or aluminum alloys in testing methods. The most common testing method is the comparison of their mechanical properties and the implementation of S-N curve diagram methods.

This paper presented the fatigue life characterization of four different technical and ceramic matrix composites used to implement the existing fatigue life methods and estimated the amplitude stress and endurance limit in a specific number of cycles until failure. The outcome of this investigation was that materials with higher ultimate tensile strength S_{ut} and higher corrected strength values S_m are estimated to have higher amplitude stress and endurance limit at a constant load and correction factors which include the size, type of loading, surface finish, temperature, and reliability parameters.

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