DOI: https://doi.org/10.46632/mc/1/2/7

Materials and its Characterization
Vol: 1(2), 2022
REST Publisher; ISBN: 978-81-948459-0-4
Website: http://restpublisher.com/book-series/materials-and-its-characterization/

Review Study on Mechanical and Thermal Properties of Ceramic Materials for Future Aerospace Applications

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Abstract. We are investigating the usage of ceramic materials in the aerospace sector. Ceramics are being used in a restricted number of aeronautical structural applications. Ceramics brittleness, lack of malleability, and expensive cost has been key deterrents to their widespread usage. We can determine the mechanical and thermal properties of this material by studying its mechanical and thermal properties such as strength, hardness, elasticity, grip and fracture, and thermal conductivity, diffusivity, thermal expansion, coefficient of expansion, and diffusivity. Some ceramic materials offer qualities that are important in aerospace applications, as well as the benefits and drawbacks of employing ceramic in the aerospace sector.

Keywords: Aerospace, Applications, Ceramics, Properties

1. Introduction

Accurately determining a ceramic material's qualities allows it to be matched to appropriate applications; hence, rapid and accurate methods for forecasting material attributes would be immensely valuable. Various modeling approaches may be used to forecast material qualities based on compositional and processing information, producing quick and reliable results. We found that ceramic materials are employed in a limited number of aeronautical structural applications after examining their utilization in the aerospace business. Ceramics are not widely employed in a variety of applications due to their brittleness, lack of malleability, and high cost. We can identify this material's mechanical and thermal qualities by researching its mechanical and thermal properties such as strength, hardness, elasticity, and fractures developed which would help in the usage of ceramic materials in aerospace industry which will help in replacing many heavy materials with the light and high temperature resistant ceramics. This paper completely discussed the mechanical properties and thermal properties of ceramic materials for its application in the aerospace industry.

2. Literature Review

E. A. BUSH et.al (1958) Temperature and thermal history were used to determine the thermal expansion, modulus of rupture, and elasticity of magnesium di- titanate. The values rose as the temperature climbed up to 1000°C, and hysteresis effects were seen after cooling. These occurrences were linked to the formation and recombination of interior fractures caused by strains caused by the significant anisotropy of thermal expansion of magnesium titanate.[1] R. W. DAVIDGE et.al (1969) Ceramic material strength and fracture behavior are explored with particular emphasis on oxides. Most materials have strengths that are around two orders of magnitude lower than their theoretical strengths, and ceramics are particularly brittle when they break. The crucial variables in the helpful Griffith equation for discussing strength are effective surface energy and starting fracture size. These two elements could be related to microstructural traits. The structure is not especially sensitive to the effective surface energy. Although the regulating factors are still poorly understood, the Griffith crack size is more structure-dependent. For future progress, a deeper understanding of the relationship between Griffith fractures and grain and phase boundaries is required. [2] J. Woirgard et.al (1998) describes A device with nanoindentation capabilities that enables the application of forces between a few micronewtons and 100 millinewtons. The device's primary goal is to provide quick and accurate readings in a typical laboratory setting. Various findings about the nanoscale plasticity in some ceramic materials are provided.[3] William A. Curtin et.al (1991) The pullout work and ultimate tensile strength of ceramic-matrix composite (CMC) materials evaluated under uniaxial stress are predicted using a theory. Assuming that each fiber fractures on its own, global load redistribution happens when a fiber breaks. Trends in these composite characteristics as a function of the sliding resistance T, the fiber radius, and the statistical fiber strength are evident.[4] Aira Kawasaki et.al (1994) has reviewed on advanced materials which is characterized by composition and microstructural gradation.This advanced materials are known as FGM.[5] Yahong Liang et.al (2001) explains that Advanced ceramics and technologies have potential uses in a variety of industries, from energy transmission and communication to heat engines. This study explains the development of ceramic technology and creates an Advanced Ceramics Application Tree to show present and prospective future application areas.[6] W. Krenkel et.al (2005) has studied the C/C-Si composite, this is used mainly in the parts which are in contact with high temperature. Another name for these parts is hot structures such as nose cap, engine flaps, nozzle jet vanes. Also the manufacturing technologies and enhancement of this properties are discussed.[7] M. Rosso et.al (2006) has explained about the manufacturing technologies, present applications and future application of metal matrix, advanced ceramics and metal ceramics matrix.[8] Maria MRAZOVA et.al (2013) In this thesis, the author introduces the composite materials with their advantages and disadvantages. Airbus and its innovation in composite materials are introduced in the second part of the thesis. The advent of new types such as nanotube forms is certain to accelerate and extend composite usage.[9] Todd E.Steyer et.al (2013) discussed about the ceramic technology in aerospace. He deeply elaborated the application in the field of propulsion, thermal Protection systems and hot primary structure.[10] Xuesong Zhang et.al (2018) reviewed about the material requirements for aircraft structures, advancement in aerospace materials and what is future of materials in aerospace.[11] Jon Binner et.al (2019) discussed about ultra-high temperature ceramic.Matrix composites which has huge applications on rockets.He has reviewed the selection, processing and applications of UHTCMC.[12] Sufang Tang et.al (2016) has reviewed the design, preparation of ultra-high temperature ceramic composites. This paper has given the basic idea and role of UHTC in aerospace field.[13] Zhao-Yong Jiao et.al (2016) has described the Ti-alloy NB4ALC3 in the form of solid solutions formed by doping Ti in NB4ALC3. The mechanical properties such as elasticity, brittle or ductile, and also thermal properties such as thermal conductivity, thermodynamics, phase stability are studied, as well as calculations are performed. Specially for mechanical properties experiments were performed. Another important property is that electronic structures are also examined.[14] Vivek T. Rathod et.al (2017) have reviewed the multifunctional use of ceramics and metal matrix, the polymer. Properties of ceramic matrix nanocomposite such as providing electromagnetic shielding, structural health monitoring and disadvantages, challenges in implementation and future applications in aerospace are discussed. [15] Sergiy LAVRYNENKO et.al (2018) Nanostructured ceramic materials and compositions based on them are becoming increasingly popular in many fields of research and technology. This study focuses on the synthesis of nanopowders and an efficient technique of sintering them for the creation of nanoceramic materials with unique mechanical characteristics, such as components with higher modulus of elasticity ("ceramic steel"), and so on.[16] *Jaishree* Vyas et.al (2018) Contactless measurement has become increasingly versatile and adaptive in recent years, owing to its wide range of applications. This study discusses several air coupled inspection techniques, such as transmission and guided wave production, as well as their operating modes. The benefits of air-coupled ultrasonic guided wave inspection over other NDT methods, as well as their requirements, are reviewed in relation to the materials.[17] Alexander Katz-Demyanetz et.al (2019) The paper deals with the "powder-bed" concept states that the feedstock material employed is a powder, which produces a "bed-like" platform of homogenous layer that is fused. Following that, a new powder layer of the same thickness is applied, and the "printing" process is repeated. This method is employed in laser sintering/melting, electron beam melting, and binder jetting printing. Discussion of additive manufacturing (AM) of aerospace essential parts made of titanium alloys, nickel-based superalloys, ceramic matrix composites, and high entropy alloys receives special emphasis.[18] Bogdan Stefan Vasile et.al (2020) has studied about different ceramic materials which can be utilized as coating because of their high thermal conductivity, and their aerospace applications are also discussed.[19] Al Arsh Basheer et.al (2020) has been no evaluation of smart materials for a long time. Smart materials offer distinct characteristics such as self-sensing, self-adaptability, memory capability, and a wide range of functions. This paper discusses breakthroughs in smart materials and their applications in the aerospace industry. The categorization, operating principle, and most recent advances (nano-smart materials) are all covered.[20]

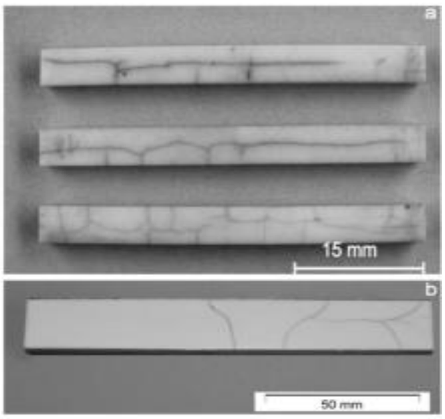
3. Mechanical Properties

Strength: The strength of a material in a specific application is determined by a variety of characteristics, including its resistance to deformation and fracture, and it frequently depends on the geometry of the member being constructed. Yield strength, tensile strength, compressive strength, flexural strength, ultimate strength, fracture strength, theoretical strength, and more forms of strength exist. In general, when temperature rises, so does the strength, which is proportional to the decrease in elastic modulus. It is, nevertheless, restricted in its intermediate temperature behavior (1000 °C). At high temperatures, the strength rapidly diminishes due to inelastic effects. Most ceramics have a lot of chemical secondary structure at the grain boundaries, which softens and reduces the hardness.[21]

TABLE 1. Maximum and Minimum values of Strength [21]

Properties	**Maximum value**	**Minimum value**
Tensile Strength	1700MPa	30MPa
Flexural Strength	965MPa	28MPa
Compression Strength	4500MPa	400Mpa
Yield Strength	1550Mpa	20Mpa

Factors Affecting Strength Of Ceramic Materials: The microstructure, the form and size of internal faults, the size and shape of the sample itself, the pace of change, environmental conditions (temperature, visibility, pH, etc.), the state of tension, and stress are all elements that impact the strength of ceramic materials. The effect of microstructure on ceramic material strength: The strength of the ceramic material diminishes as the porosity increases. The reason for this is because pores diminish the solid phase cross section, which causes the real stress to rise; on the other hand, the pores create stress concentration, which causes the strength to drop; the quantity and fracture energy change with porosity also impact the strength value. The influence of sample size on ceramic material strength: Bending strength is typically used as the strength index of technical ceramic materials. Bending stress has an unequal distribution over its thickness and length. Defects in various sites have varying consequences on strength. Bending strength is affected by size, particularly thickness. The lower the thickness of the specimen in the same volume, the higher the test strength value. The cause for the bending strength thickness impact is the same as the change in stress gradient. In general, the bigger the stress gradient and the stronger the bending strength value, the smaller the sample thickness. The influence of temperature on ceramic material strength: Most ceramic materials have strong high temperature resistance, typically below 800°C, and temperature has no influence on ceramic material strength. The strength of most ceramic materials declines with rising temperatures at high temperatures. Brittle-transition transition temperatures vary amongst materials. MgO, for example, has a very low brittle-transition transition temperature, and its strength decreases with increasing temperature almost from room temperature; AL_2O_3 has a brittle-transition transition temperature of about 900°C; and hot pressing Si_3N_4 has a brittle-transition transition temperature of about 900°C [22]. The brittle-delay transition temperature is around 1200 °C, whereas the SiC material may reach temperatures as high as 1600 °C. Because the brittle-transition temperature is influenced by factors such as the, the above rule serves as a guideline.[23] Hardness: An ability of a material to withstand the deformations such as scratch is widely defined as hardness of a material. Hardness test will be conducted on a material to find its hardness. Hardness of a Ceramic can be determined using Vickers Hardness Number. Fine Grained ceramics easily resists deformation therefore it is known as super ceramics. [24] Elasticity: Elastic modulus is a critical mechanical characteristic of materials, particularly in structural applications. This attribute describes the material's stiffness. Ceramics may have a large variation value while having the same composition since the elastic modulus of ceramics relies on porosity content. Bending tests are the most often used method for evaluating the elastic modulus of ceramics. This approach, however, necessitates specific specimen preparation [25]. Ultrasonic testing is a non-destructive testing method that uses high frequency sound waves to pass through materials. This type of testing is widely used to uncover flaws. The propagation of ultrasonic waves through materials is affected by the elasticity and density of the materials. As a result, if the density of the material is known, it may potentially be used to define material qualities such as elastic modulus. The results of experimental research based on ultrasonic testing for estimating the elastic modulus of metal are promising. The experiments were carried out on 304 stainless steel with a numerical error of 3.1%. The results show that ultrasonic testing may be used to measure the elastic modulus of metal. The propagation of ultrasonic waves through materials is affected by the material's structure. When an ultrasonic wave encounters an imperfection, such as porosity, it may be dispersed. Metals have a denser structure than ceramics [26]. As a result of the pores structure of ceramics, experimental investigations on ultrasonic testing to estimate elastic modulus of ceramics become interesting issues. The benefit of ultrasonic testing based on the pulse-echo approach is that it employs a single transducer or probe that consists of a transmitter and a receiver. Ultrasonic velocity is mostly estimated by measuring duration of flight through material thickness. Ultrasonic wave propagation, on the other hand, can be dispersed when it encounters discontinuities such as porosity. Furthermore, the frequency of the transducer is inversely linked to the wavelength of ultrasonic. The wavelength of an ultrasonic wave influences its sensitivity to the structure of the substance.[27] Grip and Fracture: Ceramic materials contain a significant percentage of ionic or covalent bonding. This causes some unusual behavior and, as a result, some unusual challenges with their reliable usage in engineering. In the temperature range of technical importance dislocations are rather stationary and dislocation induced plasticity is virtually totally absent in ceramics. This explains their great hardness and intrinsic brittleness. Ceramic fracture toughness values typically vary from 1 to 10 MPa m, and total fracture strain is often less than a few parts per thousand.[28] Fracture of ceramic components depends on many factors, e.g. the chemistry and microstructure of the material. The macroscopic appearance of fracture is, however, primarily influenced by the type of loading of the component. At low and ambient temperatures, fracture of ceramics is always brittle. An example of a typical fracture surface is given in Figure 1, which shows the forced rupture of a silicon nitride valve tested in a tensile test. The fracture origin is agglomerate related to a pore, which behaves in a similar way to a crack. In this case, the fracture origin consists of a critical flaw surrounded by rough regions called the fracture mirror and hackle. The sizes of these regions are found to be proportional to the stress in an uncracked body. There are several modes of failure in operation. The manner of loading often defines them, and each result in a distinct macroscopic fracture appearance. Nonetheless, a significant proportion of in-service failures can be attributed to just two types of failure modes: i) thermal shock and ii) contact stress. These are discussed in further depth below.



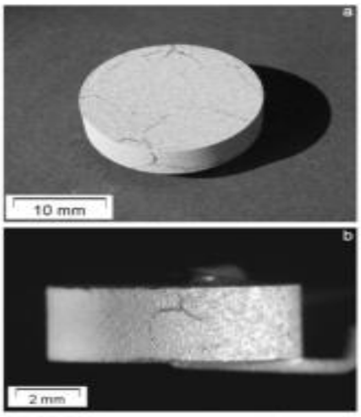


FIGURE 1. Thermal shock cracks in alumina ceramics [28]; **FIGURE 2.** Thermal shock cracks in PTC-ceramics [28]

Thermal Shock Failure: Thermal shock (or thermal shock) failure is a prominent failure mode in ceramics. More than a third of all rejections of ceramic components are caused by thermal shock. Thermal shock occurs when rapid temperature changes cause temperature differences and thermal strains in the component. If tensile stresses exceed certain critical values, damage occurs resulting in characteristic crack patterns. Examples of thermal shock damage in samples and components are shown in Fig 3 and Fig 4.When tensions become locally supercritical, thermal shock fractures form. The expansion of such fissures decreases the tensile stress in their surroundings, which acts as a driving factor for further extension. Consequently, fracture propagation may cease. The number of cracks grows in proportion to the degree of the shock. Whereas thermal shock cracks normally run perpendicular to edges, at flat surfaces (where biaxial stress states occur) they\tend to form networks, which appear surprisingly similar to the mud cracking patterns found in dried-up marshes. Crack development occurs in the opposing direction of heat flow. Thermal shock fractures may generally be identified by a simple visual inspection of the damaged component due to their distinctive appearance.

4. Contact Failure

Loading contact of hard surfaces, such as static or dynamic body impingement, can cause cracking if stresses reach critical values. Such damage often happens in one of two modes: local area loading, also known as "blunt contact," or point loading, sometimes known as "sharp contact. "Blunt contact is a common scenario that Hertz thoroughly addressed by modeling it as the contact between a sphere and a flat surface. Compressive stresses emerge in this contact region, the amplitude of which is determined by the elasticity of the two surfaces and which increases with both the applied load and the decreasing radius of the sphere. A thin ring-shaped area encircles the contact zone, where considerable tensile stresses occur. The highest amplitude of these is around 25% of the mean contact pressure if the tensile stresses locally surpass some threshold amount a ring shaped cracks (Hertzian ring crack) is created. Hertzian fractures are frequently produced by improper handling or localized overload. Fig 3(a) and 3(b) depict a Hertzian ring fracture on the surface of a silicon nitride specimen and contact damage cracks in a silicon nitride roll for rolling high alloyed steel wires. Radial cracks and a break out generated by lateral fractures coming from a Vickers indent on the surface of silicon carbide and silicon nitride ceramics are shown in Fig5(c) and 3(d). The fracture may not end then and an edge flake breaks out. Such edge flaking may often be noticed in worn ceramic components, e.g. in classical ceramic items such as marble stairs, dinnerware and tiles, but is also\seen in technical ceramic products like tool bits or guides for\shot metal sheets in steel works and even in human teeth or\tooth implants. Figure 4 depicts examples of edge flakes.[29] The contact damage detailed thus far is generated by some type of quasi static loading, although damage from dynamic (impact) loading can be fairly comparable. A hit with a rounded-head hammer, for example, can generate a Hertzian-like ring break on the component's surface. A common example is the chipping and cracking of automobile windscreens produced by the impact of grit and tiny stones. Although commonly visually displeasing, contact damage does not necessarily cause instant failure, but may serve as the genesis of some delayed failure produced by the subsequent steady or quick growth of fractures.[30]

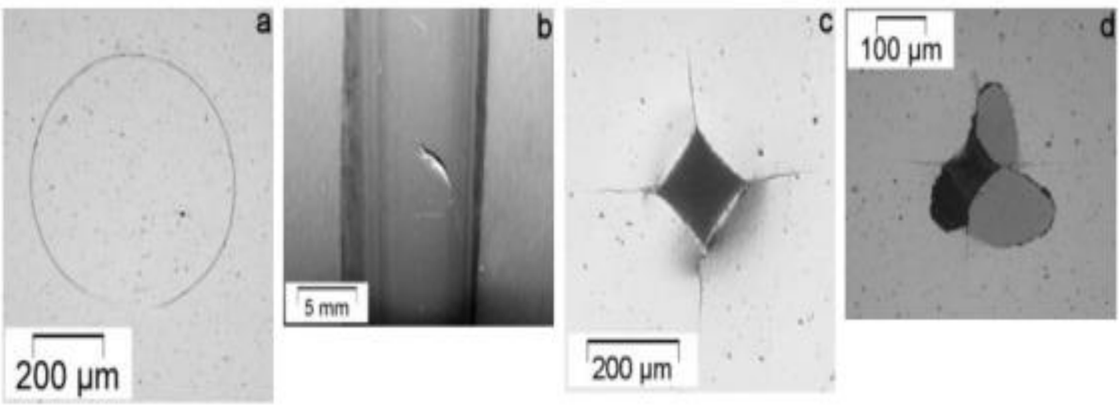


FIGURE 3. Contact damage (cracks) in the surface of ceramics [28]

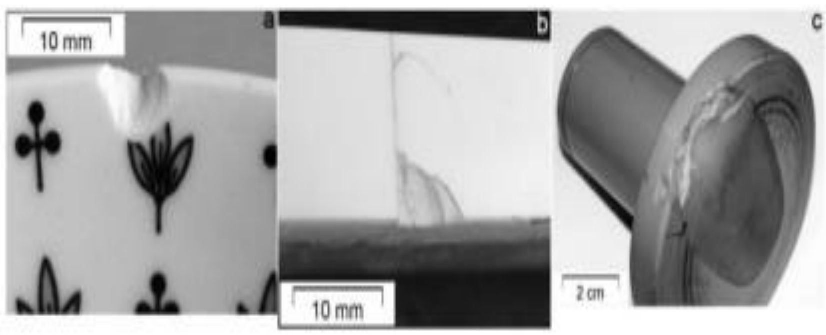


FIGURE 4. Examples of edge flakes in used ceramic components [28]

5. Thermal Properties

Thermal Conductivity: Thermal Conductivity is one of the thermal properties which measures the conduction of heat. In case of Fine ceramics, It has a mixture of low level conductivity and high level conductivity. As per the name suggests, High level conductivity means material transfers high heat and exact reciprocates for low level conductivity. Furthermore, Thermal conductivity has a huge impact on ceramic's applications. It basically determines the flow of heat.[31] Thermal conductivity of porous ceramic substances decreases with growing porosity [32].At very low temperature, the thermal conductivity will increase with growing temperature whilst at better temperature the thermal conductivity decreases with increasing temperature.[33]. Thermal conductivity of AlN is 140–180 W/mK but varies in the vary 18–285 W/mK in polycrystalline AlN ceramics relying on the manner condition, purity of beginning materials, and microstructures.[34] High thermal conductivity substances with excessive directionality in heat switch can be used in particular directional heat dissipation functions as thermal interface substances (TIM).[35] Oxides, Nitrides, Carbides and Borides are the main composition of high level thermal conductivities of ceramics. PCD, Aluminum Nitrides are some of the examples of ceramics with high conductivity. Thermal Diffusivity: Conduction is influenced by thermal conductivity and thermal diffusivity. Thermal diffusivity is a measure of heat transfer. It is measured in a medium. It is given by thermal conductivity to the product of density and heat capacity. Thermal diffusivity of a material can be determined by laser flash method.[36]The thermal diffusivity is greater than 0.2 mm2 s−1 for temperatures under 50 °C. For temperatures between one hundred °C and 350 °C the diffusivity is about 0.18–0.19 mm2 s−1, whereas it decreases for greater temperatures to values under 0.10 mm2 s−1.[37] Thermal Expansion: Thermal expansion occurs when materials are heated and their size and volume grow in tiny increments. Expansion values differ according to the substance being heated. The coefficient ratio of thermal expansion describes how much a material expands per one degree Celsius (2.2 degrees Fahrenheit) increase in temperature. Fine ceramics (sometimes referred to as "advanced ceramics") have low coefficients of thermal expansion, which are less than half that of stainless steels [38]. Advanced ceramics feature low coefficients of thermal expansion, which quantify how much a material expands as its temperature rises.[39] When heat is given to most materials, they expand according to their atomic structure; however, ceramics, due to their atomic composition, may remain stable across a larger temperature range. When compared to metals such as stainless steel, advanced ceramics have half the coefficients of thermal expansion, and this low thermal expansion may be leveraged to advantage in designing assemblies where ceramics can be held under compression to increase mechanical strength. Zirconia and Alumina have the most thermal expansion while Silicon Nitride and Silicon Carbide have the lowest.With a diverse selection of materials and grades with varied properties, materials such as shapal Hi M soft,with its near expansion match to silicon, perform well in semiconductor applications. Coefficient of Conductivity and Diffusivity: Coefficient of Thermal expansion (CTE): The amount of thermal expansion normally increases as temperature rises. At low thermal levels, the CTE should exhibit a proportionate connection between expansion and rising temperature. However, higher thermal values challenge the thermodynamic features of solid expansion, especially when components are physically limited. Because dimensional changes can cause materials to fracture and fail in such situations, low CTE materials are preferred in refractory applications with inflexible equipment or component housings. Extreme temperatures can distort CTE data, resulting in a disproportionate link between higher thermal values and volumetric change, leading to more complicated mechanical instability. This might result in harmful thermomechanical stress inside the mineral structure of the material.Because of their unique structural composition and low heat conductivity, technical ceramics often have a lower CTE than metals. Metal alloys have thermal expansion coefficients ranging from 10 to 30 x 10-6/k. Sialon ceramics have CTEs as low as 3.0 x 10-6/k, indicating extremely low sensitivity to expansion at high temperatures. This resistance to thermal expansion also allows the material to retain its physical integrity over long service lives or continuous hours of operation, whereas conventional materials may begin to show signs of thermal warping or fracture risks during long service lives or continuous hours of operation. CTE is defined as the relative increase in length per unit of temperature. Temperature increase per unit of time rise. It is represented by the following expression as- Coefficient of Diffusivity: Diffusivity, also known as mass diffusivity or diffusion coefficient, is a proportionality constant that exists between the molar flow owing to molecular diffusion and the concentration gradient of the species. [40] The diffusivity of ceramic depends on thermal diffusivity. The coefficient of thermal diffusivity was determined from measured values of the specific heat capacity, thermal conductivity, and density using the following equation derived from Fourier's law of heat conduction through solid: The thermal conductivity of the samples was evaluated using the Quick Thermal Conductivity Meter (QTM-500) with sensor probe (PD-11), which employs a transient approach (non-steady state) to analyze heat conduction. The density was estimated by measuring the size and mass of the sample, and the specific heat capacity was computed using the mixes technique. Thermal conductivity, density, and specific heat capacity were all measured at room temperature.[41]

$$\alpha = \Delta L / (L_o \Delta T) \quad \ldots\ldots\ldots\ldots \quad (1)$$

where,
α -coefficient of thermal expansion (CTE);
ΔL – length increase;
Lo – initial length;
ΔT – temperature rise.
Thermal expansion of ceramic materials is generally lower than that of metals.
For example CTE of SiC = 2.3 $°F^{-1}$ (4.0 $°C^{-1}$).
CTE of Al = 13 $°F^{-1}$ (23 $°C^{-1}$).

α = k/l ………………………………………….   (2)

where,
α is the thermal diffusivity,
k is the thermal conductivity,
l is density

6. Conclusion

A material which is not made of material or an organic is known as ceramic material. This paper as completely discussed ceramics mechanical and thermal property to make it desirable for aerospace applications. Some of the important points are Fine ceramics have low coefficients of thermal expansion, which quantify how much a material expands as its temperature rises. Ceramics can be held under compression to increase mechanical strength Temperature has no influence on ceramic material strength; most have strong high temperature resistance. The elastic modulus of ceramics is a critical characteristic of materials, particularly in structural applications. Ceramics have a large variation value while having the same composition since the material's porosity varies. Metal alloys have thermal expansion coefficients ranging from 10 to 30 x 10-6/k. This resistance to thermal expansion also allows the material to retain its physical integrity over long service lives. Coefficient of Thermal expansion (CTE): Extreme temperatures can distort the thermodynamic features of solid expansion. Metal alloys have thermal expansion coefficients ranging from 10 to 30 x 10-6/k. Thermal shock (or thermal shock) failure is a prominent failure mode in ceramics. More than a third of all rejections of ceramic components are caused by thermal shock. Contact damage does not necessarily cause instant failure, but may serve as the genesis of some delayed failure produced by the subsequent steady or quick growth of fractures. Hardness of the ceramics will be determined using the Vickers Scale.

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