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Material Selection for Gas Turbine Blade Coating Using GRANTA Material Selector

A. A. Abioye[1,2], P. O. Atanda[2], S. B. Majolagbe[1], D. A. Isadare[1,2], O. P. Abioye[2], K. J. Akinluwade[1,2*] and A. R. Adetunji[1,2]

[1]Department of Engineering, Prototype Engineering Development Institute, Ilesa, National Agency for Science and Engineering Infrastructure, NASENI, Nigeria.
[2]Department of Materials Science and Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria.

Authors' contributions

This work was carried out in collaboration between all authors. Author AAA designed the study, performed the modeling and CES EduPack selection analysis, wrote the protocol and wrote the first draft of the manuscript. Authors SBM and DAI did the literature searches. Authors OPA and KJA did the data analysis. Authors POA and ARA supervised the study and interpreted the results. All authors read and approved the final manuscript.

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ABSTRACT

This paper presents the selection of suitable candidate materials for thermal barrier coating of gas turbine blade using GRANTA software. There have been reported cases of gas turbine blade failure in service due to the extreme service conditions. Such failure could possibly have occurred due to poor material selection for thermal barrier coatings on the turbine blade thereby exposing the blade to harsh condition over time. The major adverse effects on these blades are thermal fatigue, high temperature oxidation, hot corrosion, interdiffusion, high cycle fatigue and creep.

**Corresponding author: E-mail: jakinluwade@yahoo.com;*

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1. INTRODUCTION

Gas turbines have been widely utilized in different applications most especially for power generation and aeronautics. The major purpose of gas turbine engine is to deliver mechanical power or thrust using a gaseous working fluid [1]. Advancements made in the field of materials have contributed to an improvement in the design of gas turbine engines with special materials of enhanced performance. This has led to gas turbine engines with higher power ratings and efficiency levels. Advancements in gas turbine materials have always played a prime role – the higher the capability of the materials to withstand elevated temperature service condition, the more the efficiency of the engine. It has also been noted that materials with high elevated temperature strength-to-weight ratio help in weight reduction [2].

The recent evolution in the field of materials engineering has increased the thrust-to-weight ratio of military engines to about 4 times the initial value. Commercial engines have decreased their specific fuel consumption to about 60%, while the industrial gas turbines have raised their efficiencies (simple cycle) from 20% to about 35% [3]. At high operating temperature, the gas turbine blades are experiencing extreme service conditions, the blades in that area are strongly centrifugally loaded thereby experiencing high rotational speed and vibration. The major adverse effects on these blades are thermal fatigue, high temperature oxidation, hot corrosion, interdiffusion, high cycle fatigue and creep which could lead to different failure modes in turbine blades made from superalloys. These adverse effects vary depending on the turbine operations application as shown in Table 1.

Long-term gas turbine operation leads to microstructural degradation of superalloy blades. In a number of cases, structural degradation results in a significant change in the mechanical properties, this can lead to blade failure [4]. Thermally deposited ceramic coatings on metallic turbine blades have enabled turbine engines to operate at higher temperatures and, according to the laws of thermodynamics, higher efficiencies [5]. The objective of the present work is to apply GRANTA (CES EduPack) software to select appropriate coating material to achieve thermal barrier for turbine blades. The future outlook of work is to increase lifespan of turbine blades without incurring exorbitant costs in material.

2. PROPERTIES CONSIDERED IN SELECTING MATERIALS FOR COATING

Applying a coating of a refractory insulation ceramic to metal turbine blades and vanes allows the engine to run at higher temperatures while minimizing deleterious effects on the metal blades [7]. There is the need to apply high performance coatings for their protection under elevated temperature conditions as the gas turbine blades experience high temperature corrosion [8]. Suitable candidate material must be selected by considering the function, the objectives and the required service conditions in which the turbine would be operating. Based on the following factors the material for coatings must be considered.

2.1 Temperature

The coating material to be selected must be of a high refractory to be able to withstand high operating temperatures.

2.2 Thermal Conductivity

The material to be considered must have a low bulk thermal conductivity to minimize heat transfer to the metallic blade underneath.

2.3 Thermal Expansion

The thermal expansion of the selected material should closely match that of the metallic substrate to minimize potential stresses.

2.4 Porosity

The material to be selected must have grain and pore structure that will minimize thermal conduction between the metal-ceramic interface. The material should have enough porosity to minimize the thermal conductivity.

2.5 Adhesivity

The adhesive property of the material is important to prevent spalling of the coating at elevated temperature. The coating must bond

Table 1. Severity of the different surface-related problems for gas turbine applications [6]

Items	Oxidation	Hot corrosion	Interdiffusion	Thermal fatigue
Aircraft	Severe	Moderate	Severe	Severe
Land-based power generator	Moderate	Severe	Moderate	Light
Marine Engines	Moderate	Severe	Light	Moderate

very well with the metallic blade to prevent sudden exposure to high temperature which can cause severe corrosion, creep and melting.

2.6 Density

Low density material should be selected to reduce the weight of the coating on the metal substrate.

3. METHODOLOGY

Cambridge Education Selector (CES) Granta software was used to select the suitable candidate materials for the gas turbine blade coating. This was done by considering the *function, objective and constraints* of the gas turbine blade coating. The basic function of the coating is to serve as a refractory shielding for the metallic blade from the extreme operating temperature. The objective of the coating is to be able to withstand high temperature and provide excellent adhesion to the metallic substrate to prevent the exposure of the blade to extreme conditions which could lead to severe corrosion, creep or even melting of the blade. The constraints considered for the selected materials are cost and availability. Different material properties like thermal conductivity, maximum service temperature, thermal coefficient of expansion, porosity, density, adhesivity and mechanical properties (yield strength, young modulus, fatigue strength and fracture toughness) were given consideration. Based on these functions, objectives and constraints, the material properties were plotted in bubble charts using GRANTA software and suitable candidate materials were selected.

4. RESULTS AND DISCUSSION

Each colour in Figs. 1, 2, 3, 4, 5 and 6 represents family of materials; the yellow colour code represent technical ceramics, the green colour represent foams and lavender colour represent composites materials.

The candidate materials selected for thermal barrier coatings of turbine blade were; zirconia, alumina, mullite, cordierite, graphite, carbon fiber reinforced carbon matrix composite, silicon nitride, silicon carbide, boron nitride and boron carbide.

From Fig. 1, it is seen that foams has low thermal conductivity and could withstand very high maximum service temperature unlike their ceramic counterparts with very high thermal conductivities, although they could also withstand high service temperature. The composite showed a relatively high thermal conductivity compared to foam but could not be used at a very high service temperature like ceramics and foams. The thermal expansion coefficient was almost of the same range for most of ceramics, foams and composite (Fig. 2). The chart of young modulus as a function of maximum service temperature (Fig. 3) indicated that foams have low young modulus but could withstand very high service temperature, unlike ceramics and composite which have high young modulus but could not withstand high service temperature like foams although some ceramics could. The bubble chart presented in Fig. 4 showed the specific strength; with composite having the highest ranking, followed by ceramics and foams. From Fig. 5, most of the composites have high facture toughness even at very high fatigue strength of 10^7 cycles; most of the ceramics have moderate fracture toughness at moderate fatigue strength when compared with foams. Fig. 6 shows the bubble chart of yield strength as a function of price. Based on the aforementioned, the material properties values of the selected candidate materials were as shown in Table 2 (see appendix).

The maximum service temperature of Silicon nitride is as shown in Table 2 (see appendix). Silicon Nitride can withstand temperature up to 1080-1230ºC. Above this temperature the strength is degraded and the structural reliability is very often limited due to the softening of glassy phases, which are formed at grain boundaries as a result of processing with sintering additives [9]. There are two regions in a delayed-fracture mechanism map of silicon nitride at the temperatures above 1200ºC: slow crack growth failure and creep damage rupture. This makes it not suitable for thermal barrier coatings at operating temperature above 1200ºC [10]. Silicon Carbide (SiC) family unlike Silicon nitride has better property at higher temperature. The maximum service temperature for SiC is up to 1650ºC, due to this high temperature, it could be considered for high temperature combustion chamber. Although SiC (HIP) could withstand a very high temperature but SiC foam and SiC/SiC fiber were preferred due to their low thermal conductivities. The latter exhibits good high temperature mechanical and corrosion resistance properties, its strength does not degrade at very high temperature Dinesh et al. [10]. The young modulus (1.79x 10^{11} -2.59 x10^{11} N/m^2) and the yield strength (2.08x10^8- 2.49 x 10^8 N/m^2) of SiC were low compared to 3.02x 10^{11}- 3.18 x 10^{11}N/m^2 and 4.76 x 10^8- 5.25 x 10^8 N/m^2 for Silicon Nitride which decreases drastically at elevated temperature due to the formation of glassy phase. The fatigue strength at 10^7 cycles and fracture toughness for SiC is 1.14 x 10^8 – 1.62 x 10^8 N/m^2 and 2.77 x 10^7- 3.21 x 10^7 N/$m^{-1.5}$ respectively compared to 4.05 x 10^8 – 4.72 x 10^8 N/m^2 and 4.8 x 10^6 – 5.3 x 10^6 N/$m^{-1.5}$ for Silicon Nitride. Silicon nitride and SiC/SiC fibre have no porosity but have thermal conductivities of 31.7-34.3 W/mºC and 6.8-7.4 W/mºC, SiC/SiC fibre has lower thermal conductivity. Silicon Nitride has higher density than SiC/SiC fibre as shown in the Table 2. The price of Silicon Nitride is cheaper than that of SiC/SiC fibre.

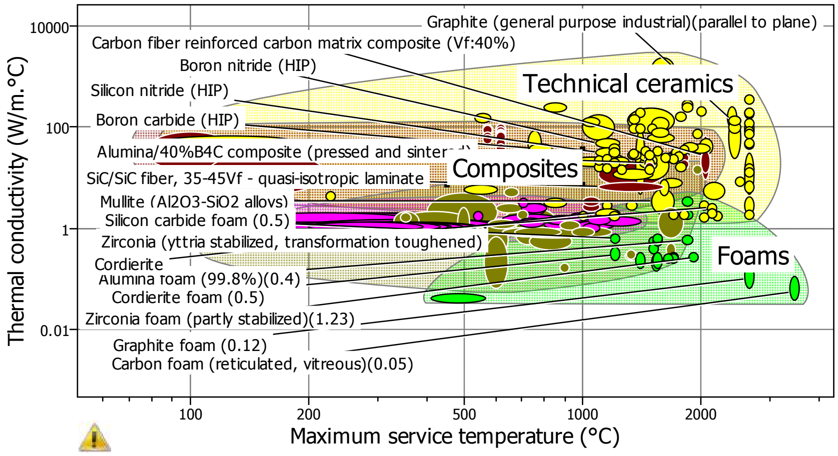

Fig. 1. Bubble chart of thermal conductivity against maximum service temperature

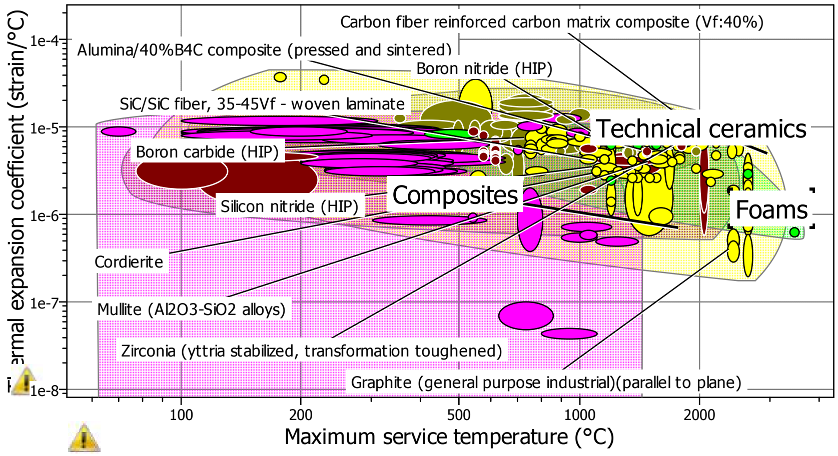

Fig. 2. Bubble chart of thermal expansion coefficient against maximum service temperature

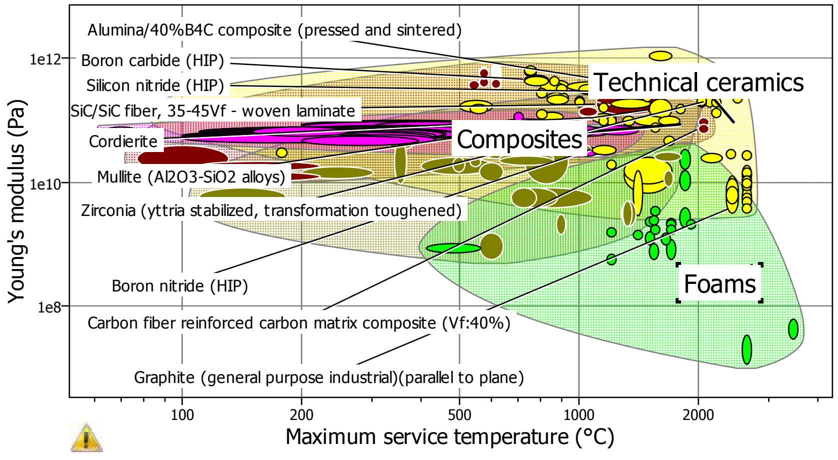

Fig. 3. Bubble chart of young modulus against maximum service temperature

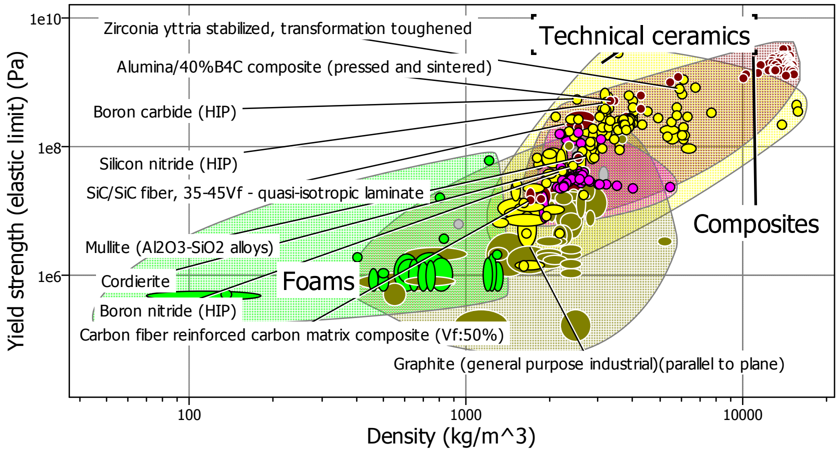

Fig. 4. Bubble chart of yield strength against density

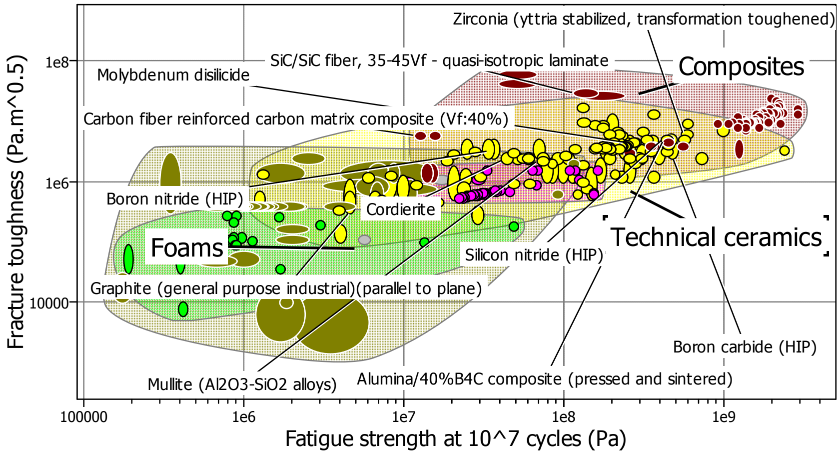

Fig. 5. Bubble chart of fracture toughness against fatigue strength

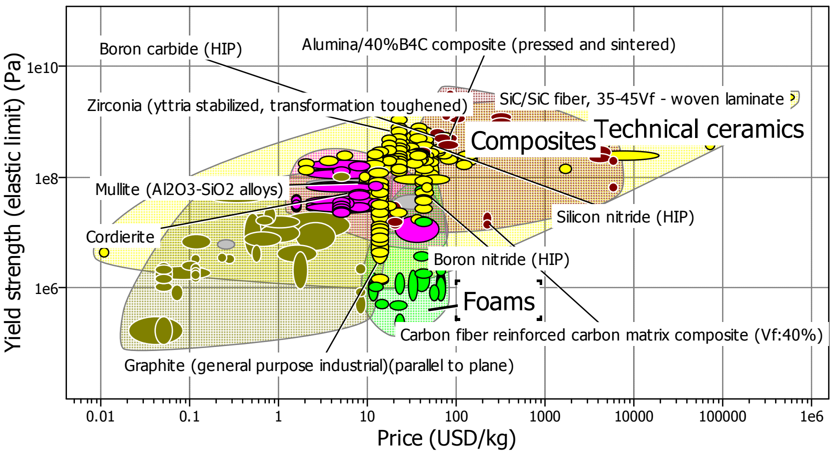

Fig. 6. Bubble chart of yield strength against price

Boron Carbide has maximum service temperature of 730-830ºC as compared to that of Boron nitride, Silicon nitride and Silicon Carbide (1230ºC). The young modulus and yield strength of boron nitride were 3.41×10^{10}-3.59×10^{10} N/m^2 and 3.97×10^{7}- 4.38×10^{7} N/m^2 as compared to 4.49×10^{11}-4.72×10^{11} N/m^2 and 5.16×10^{8}-5.68×10^{8} N/m^2 of boron carbide. The fracture toughness is the same as shown in the table but boron carbide has higher fatigue strength at 10^7 cycles than boron nitride as indicated in the Table 2. The density and price of Boron Nitride is less and cheaper than Boron carbide as shown in the Table 2. Boron Nitride and Boron Carbide has zero porosity and high thermal conductivities of 48 - 52 W/mºC and 38.4 - 41.6 W/mºC respectively, this limit their use for thermal barrier coatings.

Cordierite foam has lower density and thermal conductivity than cordierite ceramic, cordierite ceramic was considered because it has better mechanical properties and high maximum service temperature when compared to cordierite foam, the properties of cordierite ceramic were as shown in the Table 2. Carbon fiber reinforced carbon matrix composite (V_f: 40%) has excellent mechanical properties; (young modulus of 7.1 x 10^{10} - 7.9 x 10^{10} N/m^2 and fracture toughness of 5.7 x 10^{6} - 6.3 x 10^{6} N/m$^{-1.5}$). Although it could withstand maximum service temperature above 2000ºC, it has a poor oxidation resistance at temperature above 500ºC [3] which limits its use as a thermal barrier coating for temperature above 500ºC. The thermal conductivity is relatively high. Unlike other candidate materials graphite has the highest thermal conductivity which drastically limits it use. Mullite foam (NCL) (0.46) has low density, thermal conductivity and mechanical properties when compared to mullite ceramic but the mullite ceramic was considered based on the better mechanical properties which was competing with other materials in the table and has high maximum service temperature except for carbon fiber reinforced carbon matrix composite (V_f: 40%) and graphite (industrial) (parallel to plane). Alumina ceramic and alumina/B4C composite have almost the same property range; the composite would be preferred for thermal application due to its lower density and thermal conductivity and its higher yield and fatigue strengths. It has better young modulus than other materials in Table 2 except for boron carbide. Although the facture toughness is high, it is not as high as for other counterparts composites in Table 2. Its density could be a detriment. Zirconia family has good thermal conductivity and can be used at very high service temperature. Zirconia (Yttria stabilized) was considered from the family; it has very good properties with the highest maximum service temperature, density, fracture toughness, yield and fatigue strengths when compared to other materials except for its low young modulus as shown in Table 2. However, it has the lowest thermal conductivity.

5. CONCLUSION

Ceramic and ceramic matrix composite would be the best materials as thermal barrier coatings for gas turbine blades as determined from the charts. From the bubble charts and Table 2; Zirconia (Yttria stabilized) has the best properties for the service requirements with low thermal conductivity (2.5-2.7 W/mºC) and highest maximum service temperature (2080-2700ºC). One of the major challenges experienced by Zirconia (Yttria stabilized) at high temperature is phase instability. Three commonly formed phases exist in the zirconia-rich section of the zirconia-yttria binary system: cubic, tetragonal and monolithic. Under operation or forming conditions, phase transformations could occur that could cause mechanical stress and promote spalling or bond coat failure leading to exposure of the turbine blade. Another challenge is the density which would make the coating on the blade heavy, notwithstanding, the thickness of the coating is thin film in nature. Other ceramics like Silicon nitride could also be considered if the gas turbine would be operating at temperature below 1200ºC before softening of glassy phases. Boron nitride and carbide has low fracture toughness and high thermal conductivities which limit their use as coatings. Mullite and cordierite are good ceramic materials recommended for research in the area of thermal barrier coatings.

Due to the above limitations, ceramic matrix composites would be more suitable because of their good strength-to-weight ratio; and as a result of their low densities, high fracture toughness, strengths and their stability at elevated temperature. Carbon fiber reinforced carbon matrix composite (V_f: 40%) and SiC/SiC fiber could also be selected as alternative materials for thermal barrier coatings due to their very good fracture toughness, high maximum service temperature and low thermal conductivity. Although SiC/SiC fiber has maximum service temperature of 1600ºC, the fiber strength decreases at temperature above 1100ºC. It could still be used relatively above that temperature with the low strength. SiC- SiC has lower thermal conductivity than Carbon fiber reinforced carbon matrix composite (V_f: 40%). Carbon fiber reinforced carbon matrix composite (V_f: 40%) has maximum service temperature of 2000 – 2100ºC but has poor oxidation resistance at 500ºC. The solution to this problem was reliable oxidation protection using silicon nitride or silicon carbide as primary oxygen barrier, coupled with internal inhibitors and sealant. The sealant would provide effective coatings by sealing the thermal stress crack during coating. Carbon fiber reinforced carbon matrix composite (V_f: 40%) has lower density making it lighter in weight than SiC-SiC fiber. Going by these developments and considering the price; Carbon fiber reinforced carbon matrix composite (V_f: 40%) would be one of the most suitable candidate material for thermal barrier coatings of gas turbine blade when blade is made with all ceramic materials. Graphite (industrial) (para to plane) has the highest maximum service temperature but the thermal conductivity was the highest which limits its use as thermal barrier coatings for gas turbine blade. Apart from their high density; Alumina 40%B4C composite has good properties and it could be used at highest temperature in an oxidizing atmosphere and still maintain its ultimate load carrying capabilities under uncooled turbine application, it is recommended for further research.

The durability of gas turbine blade could be enhanced at higher operating temperatures without failure by selecting appropriate material for the thermal barrier coatings. The above selected materials would allow the gas turbine to operate optimally at very high temperature above 1500ºC without cooling, which is above the current prevailing gas turbine operating temperature (1200ºC).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Carlos A Estrada M. New technology used in gas turbine blade materials. Journal Scientia et Technica Año XIII, No 36. Universidad Tecnológica de Pereira. ISSN 0122-1701; 2007.
2. Nageswara Rao Muktinutalapati. Materials for Gas Turbines – An Overview, Advances in Gas Turbine Technology, Dr. Ernesto Benini (Ed.), ISBN: 978-953-307-611-9, InTech; 2011. Available:http://www.intechopen.com/books/advances-in-gas turbinetechnology/materials-for-gas-turbines-an-overview
3. Campo E-Fait Avio SPA, Torino I, Lupinc V.- CNR-ITM, Cinisello Balsamo, I. High Temperature Structural Materials for Gas Turbine. Journal Metallurgical Science and Technology. 1993;11(1).
4. Prokopenko AV, Torgov VN. Strength of Materials. 1980;12(4):520-523.
5. William W. Bathie. Fundamentals of Gas Turbines. ISBN 0471311227 Wiley; 1995.
6. Miller RA. Thermal barrier coatings of aircraft engines: History and directions. Journal of Thermal Spray Technology. 1997;35–42.

7. Matthew J. Donachie, Stephen James. Donachie Superalloys: A Technical Guide. Pag 319 ISBN 0871707497 Technology; 2002
8. Guruappa I, et al. Design and Development of Smart Coatings for Gas Turbines. Defense Metallurgical Research Laboratory, India; 2011.
9. Tatsuki Ohji. "Experimental Analysis of High temperature reliability of advanced ceramics in gas turbine" National Industrial Research Institute of Nagoya, Nagoya 463-8687. 2001;123(1):64.
10. Dinesh A. Kumar, Sathyanarayanan S, Sayantan Datta Gupta, Nageswara M. Rao. Gas Turbine Materials- Current status and its Developmental Prospects-A Critical Review; 2012. Available:http://www.academia.edu/login?cp=/attachments/5232078/download_file&cs=www accessed 03/09/2014

APPENDIX

Table 2. Values of material properties for the selected candidate materials (CES EDU PARK, 2011)

Materials	Density Kg/m^3	Porosity (%)	Price USD/Kg	Yield strength (N/m^2)	Young modulus (N/m^2)	Maximum service temperature (ºC)	Thermal conductivity (W/mºC)	Thermal coefficent expansion (Strain/ºC)	Fatigue strength at 10^7 (N/m^2)	Fracture toughness (N/m$^{-1.5}$)
Zirconia (Yttria stabilized)	5920-6040	0	18.7-27	6.43×10^{8}-7.11×10^{8}	1.99×10^{11}-2.09×10^{11}	2080-2700	2.5-2.7	1.01×10^{-6}-5.8×10^{-6}	5.47×10^{8}-6.38×10^{8}	6×10^{6}-6.6×10^{6}
Alumina/40%B4C composite	3360-3420	0	56-85	4.91×10^{8}-5.43×10^{8}	3.44×10^{11}-3.77×10^{11}	1440-1510	19.2-20.8	5.6×10^{-6}-5.8×10^{-6}	4.18×10^{8}-4.88×10^{8}	4.8×10^{6}-5.4×10^{6}
Mullite	2700-3300	0-0.2	8.29-10.4	5.5×10^{7}-1.32×10^{8}	1.1×10^{11}-2.2×10^{11}	1500-1700	2-6	3.5×10^{-6}-5×10^{-6}	6.9×10^{7}-8.05×10^{7}	2.1×10^{6}-2.3×10^{6}
Cordierite	2380-2420	0	6.22-10.4	4.8×10^{7}-5.3×10^{7}	1.07×10^{11}-1.13×10^{11}	1080-1230	1.9-2.1	2.9×10^{-6}-3.1×10^{-6}	4.09×10^{7}-4.77×10^{7}	2×10^{6}-3×10^{6}
Graphite (industrial) (para to plane)	1540-1770	0.12-.32	11.2- 17	2.8×10^{6}-9.7×10^{6}	3.4×10^{9}-12.4×10^{9}	2350-2530	113-163	4×10^{-7}-7×10^{-7}	4.22×10^{6}-4.92×10^{6}	3×10^{6}-11×10^{6}
Carbon fiber reinforced carbon matrix composite (Vf:40%)	1680-1720	11-23	207-228	1.39×10^{7}-1.53×10^{7}	7.1×10^{10}-7.9×10^{10}	2000-2100	13-35	1.1×10^{-6}-8.4×10^{-6}	1.18×10^{7}-1.38×10^{7}	5.7×10^{6}-6.3×10^{6}
Silicon Nitride (HIP)	3160-3230	0	35.3-53.9	4.76×10^{8}-5.25×10^{8}	3.02×10^{11} -3.18×10^{11}	1080-1230	31.7-34.3	3.6×10^{-6} -3.7×10^{-6}	4.05×10^{8}-4.72×10^{8}	4.8×10^{6}-5.3×10^{6}
SiC/SiC fiber	2300-2900	0	3110-5500	2.08×10^{8}-2.49×10^{8}	1.79×10^{11} -2.59×10^{11}	1100-1600	6.8-7.4	2.8×10^{-6} –5.2×10^{-6}	1.14×10^{8}-1.62×10^{8}	2.77×10^{7}- 3.21×10^{7}
Boron nitride	2190-2240	0	35.3- 51.8	3.97×10^{7}-4.38×10^{7}	3.41×10^{10}-3.59×10^{10}	1080-1230	48-52	6.8×10^{-6} –9.9×10^{-6}	3.38×10^{7}-3.94×10^{7}	2.5×10^{6}-5×10^{6}
Boron Carbide	2480-2530	0	60.1-89.2	5.16×10^{8}-5.68×10^{8}	4.49×10^{11}-4.72×10^{11}	730-830	38.4-41.6	6.5×10^{-6} –9.4×10^{-6}	4.39×10^{8}- 5.12×10^{8}	2.5×10^{6}-5×10^{6}

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