Sialon-based Composites for Solar Receivers: An overview

A. A. El-Maddah, Ahmed A. M. El-Amir[*], Emad M. M. Ewais and Y.M.Z. Ahmed

Refractory and Ceramic Materials Department, Central Metallurgical Research and Development Institute (CMRDI), Cairo, Egypt

[*]Corresponding author: E-mail: amiraelmadah@gmail.com; elamirahmed.ahmed@gmail.com

Abstract

Engineering non-oxide ceramics have recently been implied in many advanced applications based on their high temperature capability, outstanding strength, and low fabrication cost. As solar energy has become an economic trend and a clean source of energy; the utilization of ceramic materials as solar receivers in a solar thermal system has been widely considered. Various ceramic materials have shown their ability as heat absorber material due to their oxidation resistance, bending strength, thermal conductivity, and solar absorptance. Ceramics as Si_3N_4 and SiC can be valuable solar receiver materials; however, due to the high sintering temperature required for Si_3N_4 and the non-oxidizing nature of SiC; modification of these ceramics with AIN, oxide materials, and other additives is required. One of the highly promising trials that have proved its ability in a solar thermal system is modifying Si_3N_4 with Al_2O_3 and AIN that typically results in developing sialon-based ceramics. The latter materials have modified the flaws in many solar receiver ceramics as they have lower sinterability, lower fabrication cost, and easier densification compared to other solar receiver materials. The present work is an overview of the ceramic materials and composites applied as solar receivers, in addition to the characteristics required for the selected material "sialons" and the previous work achieved in this field.

Originality

This review article could be a guide for scientists and engineers concerned with developing higher efficiency of the solar thermal system by utilizing ceramic materials as solar receivers. It produces a quick and comprehensive view of the characteristics and properties required to select a ceramic material with high efficiency, and present the previous works implied at this point with further explanation of their data. Such an overview can be a starting database for developing a solar receiver ceramic material that avoids the flaws in the previous researches which can be a forward step in the renewable energy field.

Keywords: Sialons; Solar receivers; Solar power plant; Heat absorbers

1. Introduction

As the energy crisis increases along with its related environmental concerns; many alternative sources of energy are being attained to replace fossil fuels. Recently, solar energy with its sustainable feature is being considered as a clean environmental source of energy that can be a solution for the imminent climatic crisis. Solar energy can be applied as a simple source of energy that could produce as much as 7 % of the global electricity by 2030 and 25 % by 2050 with the appropriate technologies to obtain high photothermal conversion efficiency [1].

Concentrating solar power (CSP) is one of the oldest technologies between solar thermal technologies which has been developed rapidly for the solar energy field [1]. Four CSP technologies are available at present as appears in Fig. 1: parabolic trough collector (PTC), solar power tower (SPT), linear Fresnel reflector (LFR), and parabolic dish systems (PDS) [2].

An important type of CSP is SPT also known as the central receiver system (CRS) since it has low heat loss, high concentration ratio, high efficiency, and simple system [1]. It uses a field of sun-tracking reflectors called heliostats which are flat or slightly concave mirrors that reflect and concentrate the sun rays onto a central receiver placed at the top of a fixed tower [3]. Increasing the power concentration of the tower develops very high temperatures, which in turn increases the efficiency of the converted heat into electricity and reduces the thermal storage cost. In addition, various choices are available for heliostats, receivers, and transfer fluids. Also, one power block in some plants can be fed from several towers [2]. For the former, the solar tower has a crucial market position

due to its high efficiency, low operating costs, and the ability to be scaled up at large power plants.

The central receiver also known as a heat absorber or solar receiver is one of the most important parts of STPP because the efficiency of the whole system is decided based on the working temperature of receiver [1]. In the solar receiver, a heat transfer fluid (HTF) is used to absorb heat and transfer it to heat exchangers which operate a steam Rankine power cycle. Some commercial tower plants use direct steam generation (DSG) as a heat transfer fluid and molten salt as a storage medium [3].

Receivers of CSP are divided into two types; one is a linearly concentrating collector as for parabolic trough collector (PTC), that follows the diurnal position of the sun with the complete parabolic mirror structure, and the linear Fresnel collector (LFC) where the parabolic mirror shape is split up into mirror facets according to the Fresnel principle. The other is a point focus receiver as dishes and central receivers which typically operate at much higher temperatures (500–800 °C) and corresponding concentrations (500–5,000) than do linear systems [4].
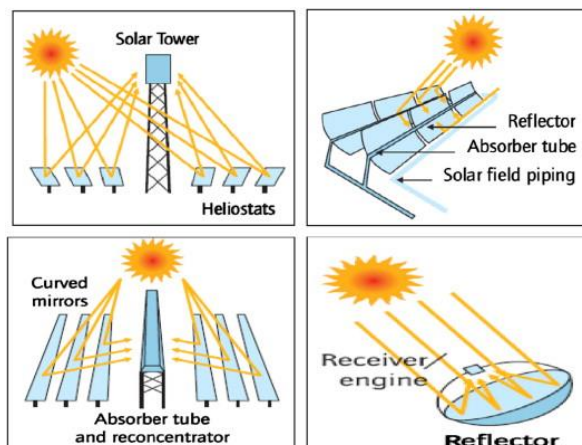

Fig. 1 Currently available CSP Technologies:(a) STP; (b)PTC; (c) LFR; (d) PDC, (With permission from Elsevier Copyright 2013) [2]

Solar absorber materials are a very important side of CSP technology (the working principle can be shown in Fig. 2), where the absorbing material receives cold air and converts it into hot air. The absorbing material must have good oxidation resistance, high thermal shock resistance, and high solar absorptance due to the special operating conditions [3, 5]. The efficiency of a CSP system depends on both, the concentrator solar convergence power and its heat absorbing efficiency. For that, an efficient absorber material is required [3].

The present review is concerned with the different ceramic materials or composites that can be used as solar absorbers in solar receivers specially sialon materials due to the outstanding characteristics that promote them to be promising candidates in such applications.
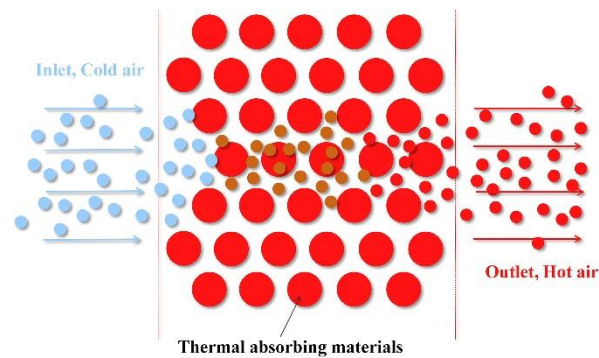

Fig. 2 Working principle of the heat absorber (With permission from Elsevier copyright 2017) [5]

2. Central Receiver for Tower Solar Concentration System

The main operating principle of the central receiver is depending on absorbing high concentrated radiation that is reflected by heliostats through a heat transfer medium and converting it into thermal energy which is then used for generating superheated steam for turbine operation [6]. Solar receivers are responsible for determining the operating temperature of power conversion and thermal processes at solar towers. Operation of engines with high efficiency requires the achievement of high operating temperatures approximately above 800 °C which leads to increasing the number of useful industrial processes. Therefore, as the operational efficiency of a system increases; the energy cost decreases by reducing the number of concentrators that must be installed for a given output which in turn reduces land requirements and maintenance. A solar receiver is a crucial component of a solar thermal power system. Its operating temperature and efficiency directly affect the entire system performance. The design of the solar receiver must meet the requirements imposed by the concentrator, the thermal process subsystem, and the power conversion. As a result, the design requirements of receivers must be related to the specific application and system configuration. The main characteristics required for a specified solar receiver are determined by the heat transfer characteristics (depending on the working fluid), the pressure and temperature (required by the thermal process subsystem or power conversion), the mechanical configuration of the solar system, the optical characteristics of the concentrator, and the

available materials. Generally, maximizing the efficiency is the required target to design an acceptable cost of mass production and to extend a lifetime of about 20 to 30 years with the possible minimum maintenance [7].

3.   Material Used for Solar Receivers

The heat transfer or storage media materials used in central receivers are; gas as air, liquid (as water and molten salt), and solid media as ceramic particles. Receivers with liquid bases usually use panels of tubes that are irradiated by centering sunlight and cooled by flowing fluid. Those panels of tubes can be arranged as a central or cylindrical configuration or placed inside a cavity receiver. Water and direct-steam central receivers have commercially prevailed because they decreased expenses and energy losses related to the heat exchange between the power block and receiver. However, high-pressure steam is difficult to be stored with these receivers. On the other hand, molten salt temperatures can be raised higher (up to ~600 °C for nitrate salts) and stored, but the heating process must be traced throughout the system to avoid freezing of the molten salt which takes place at up to 200 °C temperatures [8].

The main idea of receivers is their ability to heat the air or other gases to high temperatures for Brayton power cycles or heating the storage media as solid particles, graphite, concrete, and phase-change material. The heating process can be achieved by using tubes, however; it can limit the heat transfer from the tube walls to the gas which is considered a drawback in these systems. Volumetric honeycombs and channels can be also used where they can be irradiated by concentrating sunlight and the air is thereafter drawn and heated as it passes through it. However, the outer part of the volumetric receiver was noticed to be hotter than the inside one which in turn results in a significant radiative loss to the environment [8, 9].

Receivers that typically use small solid particles to be heated by concentrated sunlight, eliminate heat transfer resistance and flux limitations since they are directly irradiated. These particles can be heated to temperatures above 1000 °C, stored, and applied for electricity production or heat processes [8].

Although the metal materials used as particles in receivers have good processing formability and high thermal conductivity; their low melting temperature limits their use in a system exceeding 1000 °C temperature [10]. To overcome such a problem; ceramic materials with their high melting temperature can be used as solar receivers.

4.   Ceramics for Solar Receivers

Structural ceramics have high temperature capability with nonstrategic nature and potentially low cost which make them promising candidates for solar applications [7]. In order to feed a gas turbine at operating temperatures (900–1300 °C); the temperature of the receiver wall should reach at least 1000 °C [11]. Ceramics can be applied in metallic solar receivers as a high temperature absorber coating and also can be applied directly in bulk ceramic solar receivers. Specific properties of ceramic materials are required to be used as solar receivers. They are required to have (1) high thermal conductivity to enhance the heat transfer to the fluid and to limit internal gradients; (2) appropriate optical behaviour to maximize the absorption of solar flux; (3) low expansion coefficient that minimizes deformations, fracture toughness and creep resistance; and (4) higher corrosion and oxidation resistance [12].

4.1 Characteristics of Ceramics Receivers

The main characteristics required to select a ceramic material for solar receiver applications are briefly as follows:

4.1.1   Tensile strength

Ceramic materials used in solar receivers must exhibit tensile strength for high pressures. Brittle solids are basically weaker in tension than in compression due to their lack of plasticity at crack tips. Materials with brittle behaviour are very sensitive to the relatively small flaws such as pores or other defects characteristic of fabrication. The tensile strength of structural ceramic and conventional moduli of rupture are depending on the test procedure as well as the actual strength value of the material [13].

4.1.2   Fracture toughness

The resistance of a material to the propagation and crack formation is defined by toughness. For solar receivers, toughness is the ability of a material to absorb energy before failure. Ceramic materials have intrinsic brittle nature. Their brittle nature has been excluded after the presence of ceramic matrix composites which are new materials with considerable high reliability and fracture toughness compared to monolithic ceramics. These composites can be potential alternatives to many structural engineering components [14].

The thermal stress causes rapid fracture when it exceeds the failure stress of the material. The fracture in brittle materials occurs excessively in tension behaviour due to the high ratio of compressive to tensile strength. However, the fracture due to compressive

stresses has a high occurrence due to external constraints. Generally, brittle materials are exposed to fracture failure from pre-existing cracks. The rapid failure can be assessed in terms of the critical stress intensity factors for the materials, in addition to the crack size, geometry, and the appropriate thermal stress intensity factor [15].

4.1.3   Thermal shock resistance

Thermal shock resistance is known as the ability of the materials to resist damage when they are exposed to a sudden change in temperature. For materials used as solar absorbers; their thermal shock resistance must be high due to the working condition. The thermal shock resistance has many factors that affect it, such as microstructure, phase composition, thermal expansion coefficient, fracture energy, thermal conductivity, and elastic modulus. Sudden cooling causes a shrink of the sample surface in a very short time, which in turn causes tensile stress from the internal part. In contrast, the compressive stress would occur instantly when the sample is heated severely. For ceramics that are used as solar receivers, rapid cooling is a drawback and affects harmfully due to their fragile nature [1].

4.1.4   Fatigue resistance

Fatigue failure is a mechanism that needs to be counted in the design of ceramic solar receivers. It occurs because of the growth of sub-critical cracks at steady state or cyclic stress levels below those required for fast fracture. The growth of such a crack occurs at a temperature near room temperature due to stress corrosion reaction and could be accelerated if there are surface-active molecules. Subcritical crack growth can appear by diffusional phenomena such as the rate of the surface, grain boundary, and bulk diffusion which becomes ratable at high temperatures. By using the kinetics data of subcritical growth, the fatigue-life in terms of time or cycles to failure can be determined. The rate of crack growth can be described by many expressions; the following is one expression that can be used where V is given by:

$$V = AK_I^n exp\,(-Q/RT)$$

Where A and n are numerical constants, K_I is the stress intensity factor and Q is the activation energy for the process responsible for the crack growth. Therefore, calculations of fatigue life for a given material require values of A, n, and Q [15].

4.1.5   Creep strength

The creep behaviour is measurable even in the most refractory ceramic materials at sufficiently high temperatures and modest stresses. A combination of creep deformation of the refractory major phase or phases and a creep caused by grain boundary phases normally occurs in refractory ceramic. The creep deformation of the refractory major phase or phases is more common in many ceramic applications. The fabrication of ceramic has been facilitated by employing less refractory grain boundary phases. Materials that are used in 1300 to 2200 °C regimes must be carefully evaluated with consideration of the relation between secondary grain, boundary phase composition and content as well as creep properties. Materials are differentiated from each other according to their extrinsic characteristics such as microstructural features including grain size, porosity, and the present amount and type of amorphous grain boundary phase, but generally, they are unrelated to the intrinsic properties such as compositional or crystal structure variations. The strength and rigidity of most refractory oxides rapidly decrease above 1000 °C and exhibit significant plasticity above 1300 °C but notably beat metal alloys in this temperature regime. For instance, Inconel has a creep rate under a 100-psi stress at 1100 °C compared to the creep rate of magnesia under a 1200-psi stress. Furthermore, zirconia, alumina, and silicon carbide are significantly more resistant to creep behaviour than magnesia. [13].

4.1.6   Stability at elevated temperatures

Stability at elevated temperatures is a required feature of ceramics that are used as solar receivers. Temperature is related to many characteristics such as; creep behaviour which is of utmost importance, as well as erosion and wear phenomena which are related to the system, especially if the component comes into contact with other solids, liquids, and high-pressure gases. Any combinations of creep, fatigue, wear, erosion, and corrosion phenomena are possible, which may misevaluate the response of the material under those circumstances [4].

Sharp temperature applied to solar receiver ceramics may also lead to thermal stress phenomena which are normally produced from non-homogeneous heat transfer. Such phenomena can appear as a result of the change in thermal expansions in different parts of the ceramic body under various conditions. Thermal stress is also caused by the non-equilibrium physicochemical processes that occur in a body during its manufacture or use. Many factors can affect the values of thermal stress durability and thermal stress resistance such as grain size, porosity, and ceramic additives [16]. Generally, ceramics used as solar receivers must show a stable behaviour at elevated temperatures, since their strength at such temperature decreases and stress corrosion can be more severe which leads to strength

degradation. For example, Si_3N_4 and SiC ambient temperature strengths decrease as they are exposed to oxidizing environments at 1000-1400 °C for several hundred hours [4].

4.1.7   Oxidation and corrosion resistance

Oxidation resistance is affected by phase composition, chemical composition, and microstructure. It is characterized by the weight gain rate, where the sample possesses poor oxidation resistance as its weight gain rate increases and vice versa [1]. The corrosion resistance of ceramics depends on many factors such as the surface texture, chemical nature of the major and minor phases, porosity, and mechanical damage that occurs along with processes such as erosion and wear. The corrosion resistance of a specific ceramic phase is depending on the charge density, atomic bond strength, and the transfer of electrons at surface active sites. The major phase may resist corrosion in a specific environment, but the minor phase or impurities placed at grain boundaries may corrode easily. Thus, pitting and porosity will be the result of corrosion that proceeds from locations of flow resistance causing failure and strength degradation. Corrosion resistance may also decrease by impurities and additives. For instance, less than 1 wt. % of MgO added as a sintering aid in Al_2O_3 can cause an intergranular attack in acidic environments despite the high resistance of alumina to most acids. Rough surfaces and porous regions increase surface area and facilitate penetration which in turn decreases corrosion resistance. Elevated temperatures usually accelerate corrosion; however, oxidation of porous Si_3N_4 is an exception since a continuous protective silica layer forms at temperatures above 1200°C, which decreases the rate of oxidation. The silica layer is dissociating, allowing oxidation if the atmosphere reduced or low oxygen partial pressure occurred. On the other hand, protective silica films react with alkali oxides such as soda (Na_2O) at high temperatures. As these films are contaminated with Na_2O, higher oxygen diffusivity and lower viscosity occur. In turn, a recession appears at the surface of SiC or Si_3N_4. Corrosion or oxidation can be decreased or completely eliminated by the formation of protective layers. Besides Si_3N_4, there are other known examples as SiC and $MoSi_2$ that are used as heating elements to supply temperatures up to 1700 °C due to the formation of the SiO_2 protective layer at the surface of these materials at oxidizing atmospheres and elevated temperatures [4].

4.1.8   Commercial availability at reasonable cost

The main drawback of using ceramic materials is their high cost. The reason for the high cost is implied in the high rejected levels during the production of components. These high rejected levels are basically caused by structural imperfections, especially surface, and internal flaws. The number of rejected parts during production can be reduced by increasing the fracture toughness levels. As a result, the reliability during service will enhance; that's why toughening of ceramics has been considered in many researches [17].

4.1.9   Fabricability, including joining techniques

Ceramic materials used in solar receivers are fabricated by a limited number of procedures [13]. Mechanical joining, brazing, and solid-state bonding are the highest potential joining methods. Mechanical joining is used to produce a component with repair and replaceability features. Brazing and bonding are permanent bonding techniques that are used for component or module build-up. For metal-ceramic contacts, mechanical joints are used almost exclusively. The metal surface can be coated with an inert material such as flame sprayed with Al_2O_3 to prevent diffusion of metal into ceramic and vice versa. Mechanical joints are applied exclusively for systems with moderate internal pressures and loads. They should be suitable for the pressure range of modern gas turbines, where the maximum pressure of systems generally does not exceed 250 psi. The main disadvantage of brazed joints is that; the service temperature of the brazing material is much lower than the ceramic itself. Silicon metal is a brazing material that is commonly used for high-temperature applications. Using silicon metal can limit the maximum steady-state operating temperature to about 1200°C and the short-term exposure to about 1350 °C. Brazing with silicon works specifically well for siliconized silicon carbide, which already has 10 % free silicon. Solid-state bonding is usually applied by using a cement of the same composition as the ceramic. The same firing temperature must be used for the joints as well as for the ceramic. Unfired ceramic components can also be joined by this manner to avoid firing the material twice. The original ceramics strength is higher with 10-20 % than that of the solid-state bonded joints due to differences in the number of SiC bonds formed, percent Si content, and joint irregularity on the surface [18].

4.1.10   Solar Absorptance

The materials used as solar heat absorbers should have high solar absorptance since they absorb heat from the heliostat field. The most important wavelength range on the ground for solar irradiation application is 0.3–2.5 µm because the wavelength under 0.3 µm and above 2.5 µm can be absorbed by the ozone, vapor, and

other atmospheric molecules in the atmosphere. So, the solar absorptance (α_s) in the wavelength range of 0.3–2.5 μm can be determined according to the following equation [1, 19]:

$$\alpha_s = \frac{\int_{0.3}^{2.5}[1 - \rho_s(\lambda)] \times E_s(\lambda)d\lambda}{\int_{0.3}^{2.5} E_s(\lambda)d\lambda}$$

Where $\rho_s(\lambda)$ is the reflectivity, λ is the wavelength, and $E_s(\lambda)$ is the intensity of solar radiation [19]. The absorption of light by materials occurs due to the transition of valence electrons and the vibration of atoms caused by the increased temperature from sunlight irradiation. A composite is said to have a good solar heat absorbing if it has high solar absorption in the whole UV–Vis–NIR region [1].

4.2 Types of Ceramics Receivers

Structural ceramics that are of potential interest for solar receivers may be classified into three major categories: (1) oxides; (2) alumino-silicates and (3) silicon carbides as well as nitrides [7].

4.2.1 Oxides

Oxides are not widely utilized for solar receiver applications due to their low thermal conductivity and hence poor thermal shock resistance which leads to poor heat transfer ability. However, since they have some other advantages such as resistance to oxidation, availability, and good characterization, they have been applied as solar absorbers when blended with other materials. For instance, metal oxide nanoparticles such as copper oxide and cobalt oxide nanoparticles (CONPs) either neat or in blends with other materials are widely utilized as solar absorbers [7]. Copper-cobalt oxide composite thin films have been studied for selective solar receiver applications with promising results [20]. Many researchers prefer cobalt oxide than copper oxide since they are easy to be synthesized and stable at high temperatures [21]. For example, the two forms of cobalt oxides (CoO and Co_3O_4) are stable above 5000 °C. Cobalt oxide nanoparticles are highly recommended for electronic devices, electrochromic devices, solar absorbers at high temperature, gas sensing, magnetic materials, and energy storage batteries [3]. Beryllium oxide is a ceramic material with notably good thermal shock resistance and some desirable properties. Its thermal conductivity at 1200 °C is up to four times higher than that of Al_2O_3 which gives BeO a significant better thermal shock resistance, but its tensile strength and thermal expansion coefficient at room temperature are comparable to Al_2O_3. However, BeO has a rapid decrease in tensile strengths above 1100 °C and significant restraints were placed on

manufacturing operations of this material due to toxicity reports of fine beryllia powder. Hence, those drawbacks have limited BeO consideration as a serious candidate material [13]. Numerous sensible oxide ceramics, such as alumina (Al_2O_3), mullite, zirconia, and cordierite are suitable for sensible heat storage due to the high heat capacity, the high refractoriness (>1000 °C), the good corrosion resistance against heat transfer fluid (usually air), and the good thermochemical stability. The thermal storage processes in case of using ceramic materials; proceed at a large temperature range of 200-1000 °C due to their high refractoriness. In addition, a high heat capacity is required; to reduce the volume of containers for thermal storage materials and raise thermal storage efficiency. Improving oxide ceramics to be utilized in solar applications depends on improving their thermal conductivity which can be achieved by introducing non-oxide ceramics with high thermal conductivity, such as SiC, BN, or Si_3N_4, into the oxide ceramic matrix for thermal storage applications [22].

4.2.2 Alumino silicates

The alumino-silicates are materials with moderate to good strength and can be fabricated into complex shapes, such as honeycombs to be widely used in catalytic converters with automotive exhaust gas. Their thermal expansion coefficient is very low and they have good thermal shock resistance. However, they are usually used at low temperatures and have relatively low thermal conductivities. The three common alumino-silicates are LAS: lithium aluminum silicate (β-Spodumene or β-eucryptite), MAS: magnesium aluminum silicate (cordierite), and AS: aluminum silicate (mullite). Mullite has good strength and good durability at relatively high temperatures, but it does not have good thermal shock resistance. LAS and MAS have comparable properties, with excellent thermal shock resistance. The alumino-silicates have been successfully utilized in heat regenerator designs. They are most notably utilized in rotary regenerators which are used for advanced gas turbines that are being developed for automotive applications. The alumino-silicates are considered as candidates to be used in solar receivers for operation at temperatures below 1200 °C [7].

4.2.3 Silicon carbides and nitrides

Silicon carbide (SiC) is known for its high absorption rate which makes it one of the most attractive materials to be used as solar absorbers [20]. However, SiC-based materials are non-oxygen containing compounds that may be oxidized in a high-temperature environment. Besides, the sintering temperature of SiC-based

material is high, which raises the fabrication cost. Therefore, it is necessary to develop other alternative solar heat absorbing candidates [1].

SiC yield and mechanical properties can be improved for solar applications by using additives such as silicon. Lao et al. have improved the yield of SiC for solar thermal storage by adding Si to consume the silica residual in Al_2O_3-SiC_w composite ceramics, using aluminum-assisted carbothermal reduction method which in return improved the properties of the composites. The sintered composite at 1600 °C with 5.6 wt. % Si has higher density, bending strength, heat capacity, and thermal conductivity, in comparison with the values of the basic formula which have 0.8 wt.% of Si. Furthermore, the increase of Si can overflow the surface of samples and reduce the carbon sources as well as the SiC content. The overflow phenomena appeared in Fig. 3 on the surface of the CA4 sample which has 8 wt. % of Si additives (note the white circles in Fig. 3) where molten globules were found. Also, a slight overflowing can be observed on the surface of CA3 (with 5.6 wt. % Si additive) which indicates the presence of a small amount of Si [22].
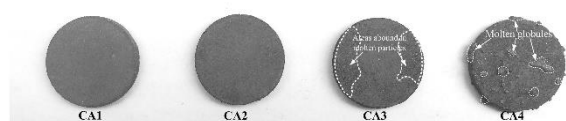

Fig. 3 Surface photo of series CA fired at 1600 °C (With permission from Elsevier copyright 2017) [22]

The addition of AIN to SiC can enhance the lack of reliability and toughness which SiC ceramics are suffering from. The lack of reliability and toughness is related to the reaction between SiC and AIN that typically yields an extensive complete solid solution. The similarity of structure and high temperature properties of SiC and AIN can highly enhance their durability and mechanical performance [23]. Besisa et al. have produced high density SiC/AIN composite with high thermal properties via pressureless sintering technique and by using AlN, α-SiC, and β-SiC as raw materials with Y_2O_3 and Al_2O_3 additives (to increase the level of density). It has been found that 2080 °C sintering temperature for 2 h can produce a high dense and promoted SiC/AIN receiver with the addition of 2.5 wt. % of Y_2O_3 and Al_2O_3. The densification behavior and AIN content have controlled the composite characteristics. In addition, increasing the temperature has enhanced the thermal expansion coefficient, diffusivity, and thermal conductivity values. The authors have nominated the resulting composites to be applied in solar energy applications [23].

Besides the former, SiC and Si_3N_4 have shown excellent properties for solar applications, such as good thermal shock resistance, high strength, high wear resistance, and thermal conductivity. However, producing dense Si_3N_4 ceramic can be very difficult with classical sintering technologies due to the high degree of covalent bonding. In addition, pure Si_3N_4 has poor oxidation resistance [20].

For obtaining Si_3N_4 ceramic with good dielectric properties and thermal insulation as well as good machinability and erosion resistance, porous Si_3N_4 ceramic can be coated with a dense Si_3N_4 ceramic to enhance the tightness and the resistance to erosion [21]. Such a design was applied by Wang et al. in which a dense β-Si_3N_4-based ceramic was coated on the porous Si_3N_4 ceramic by using the liquid infiltration and filling method at 1800 °C. The erosion resistance of the porous Si_3N_4 ceramic was improved and only 0.7–1.0 wt. % mass loss of the coated porous Si_3N_4 ceramic occurred after 2 h of eroding. The coated Si_3N_4 was not applied for solar applications, but according to the mentioned features it might be considered for such applications with further studies of its properties [21].

The performance of Si_3N_4 can be greatly improved by applying a combination phase of $MgAl_2O_4$–Si_3N_4 composites that have been fabricated by Wu et al. via pressureless sintering and in-situ synthesis technique using α-Si_3N_4, α-Al_2O_3, and MgO as starting materials. The sintered composites at 1620 °C have shown the best oxidation resistance as well as higher thermal shock resistance and solar absorptance than Si_3N_4 ceramic prepared by the same method. In this regard, these composites are highly recommended as good solar heat absorbing candidates [20].

Moreover, according to Zhang et al. adding 1 wt. % of Sm_2O_3 to $MgAl_2O_4$-Si_3N_4 pressureless sintered composites can enhance microstructure and stability at high temperatures. Sintering of the composite at 1620 °C with 1 wt. % of Sm_2O_3 additive has resulted in 339.4 MPa bending strength value, 92.0 % solar absorptance, and no damage after thermal shock [5].

Liu et al. have modified Si_3N_4-SiC composite to be used for tower type solar thermal power plant via pressureless sintering process at 1480 °C using Si_3N_4, SiC, andalusite as starting materials and additives such as Cr_2O_3, ZrO_2, and Y_2O_3. The composite had shown a bending strength of 100.26 MPa, thermal expansion coefficient of $4.561 \times 10^{-6} °C^{-1}$, and oxidation rate constant 1.7389 $mg^2cm^{-4} \cdot h^{-1}$. The authors indicated that the composite additives as Cr_2O_3, Y_2O_3, and ZrO_2 have obvious effects on the formation of reticular structure phases which are good for the increase of thermal shock resistance and oxidation resistance [24].

The main drawback of using Si_3N_4 in solar applications is its strong covalent bonding that makes its sintering process hard. However, additives like Al_2O_3 and AlN can be implied to decrease the sintering temperature. In the meanwhile, adding Al_2O_3 and AlN additives to Si_3N_4 can form sialon materials which have a high oxygen gradient that could improve the oxidation resistance of Si_3N_4 [1].

4.2.4. Sialon for Solar Receivers

The promising way to solve the aforementioned disadvantages of silicon nitride ceramics is to partially substitute Si-N bonds by Al-O bonds in a Si_3N_4 hexagonal crystal structure which forms solid solutions of Al_2O_3 and Si_3N_4 that are so-called alumino-silicate oxynitrides (sialons). Besides the fact that sialons have properties comparable or even better (in some properties) than silicon nitride, they have better sinterability, low-cost fabrication, and easier densification compared to silicon nitride ceramics. The presence of alumina in the starting mixture facilitates the formation of Si-Al-ON liquid phase with a lower viscosity which eventually enhances material densification. Moreover, the lower superplastic deformation temperature of sialon (1200 °C) with its higher strain rate (10^{-2} S^{-1}) compared to that of silicon nitride (1600 °C and 10^{-4} S^{-1}, respectively) makes their machining into a complex shape much easier and cost-effective [25, 26]. Sialons can be utilized as solar receivers since they have superior properties that are required in these applications, such as high temperature resistance, high strength, good thermal shock, and oxidation resistance. All the previous features come along with the low sintering temperature that makes them a more promising candidate than Si_3N_4.

Rare-earth oxides (R_2O_3), such as La_2O_3, Gd_2O_3, and Y_2O_3, have been introduced to form a low-melting-point eutectic R–Si–O–N liquid with Si_3N_4 powder to reduce the firing temperature and porosities of Si_3N_4 ceramics [27]. By using pressureless sintering method, Wu et al. have prepared O-Sialon/Si_3N_4 ceramic composite for solar absorbers from Si_3N_4 and low pure Al_2O_3 with different rare-earth oxides (i.e., Yb_2O_3 and Gd_2O_3). Sintering at 1600 °C with the addition of 6 wt. % of Gd_2O_3 have exhibited; more O-Sialon content, 23.29 % porosity, 105.57 MPa bending strength, weight gain rate 17.49 mg/cm² (at 1300 °C for 100 h), 75.16 % solar absorption, 10.10 % water absorption, and high oxidation resistance. The previous results had made Gd_2O_3 a better additive when compared with Yb_2O_3. The bending strength has shown a strong relation with sintering temperature as well as the rare earth oxide content. The highest value of bending strength was obtained at 1600 °C for the composite containing 6 wt.

% of Gd_2O_3. It was also found that; composites with lower weight gain values exhibited higher oxidation resistance values [27].

Wu et al. have synthesized β-Sialon/Si_3N_4 composites via pressureless sintering method at 1580 °C using α-Si_3N_4, calcined bauxite, and AlN as raw materials with Y_2O_3 and La_2O_3 as sintering additives. They have reported that adding 3 wt. % of Y_2O_3 and 3 wt. % of La_2O_3 as additives; exhibits the best mechanical properties with bending strength of 138.36 MPa. The thermal conductivity and solar absorptance values were 7.96 W/mK and 91.10 %, respectively. The weight gain rate after oxidation that reported at 1100 °C for 100 h, was as low as 0.9331 mg/cm². The composite is rather suitable to be used as the heat absorbing material in STTP systems [1].

Reddy et al. have prepared porous sialon ceramics with pressureless sintering at 1700 °C for 4 h in a nitrogen atmosphere, by adding starch in the range of 0-5 wt. % to a commercial grade Syalon 101 powder that has basic composition of 90 % silicon nitride (α-Si_3N_4), 1 % aluminum nitride (AlN), 3 % aluminum oxide (α-Al_2O_3), and 6 % yttrium oxide (Y_2O_3). As the level of porosity increased the strength and hardness of sialons were decreased. Whereas, an increase of the fracture toughness trend was observed in the host material as the porosity that was left by starch increased. The authors indicated that the resulting porous sialon has shown a promising combination of dielectric and mechanical properties, making them applicable for applications like heat exchangers which in turn can be used for solar receivers. However, further studies can be applied to assure the ability of the material to act as a solar absorber such as its thermal conductivity, solar absorbance, and oxidation resistance [28].

In a work under NASA contracts to improve Si_3N_4 based ceramics, Ashbrook et al. have improved the strength and, incidentally, the oxidation resistance of β-sialon by using pressureless sintering at 1370 °C and starting materials as 90 % α-Si_3N_4, 99.9 % A1N, and Al_2O_3 with sintering additives such as CeO_2, Y_2O_3, ZrO_2, $AlPO_4$, $GaPO_4$, HfO_2, and Cr_2O_3. Additives as CeO_2, Y_2O_3, and for the most part ZrO_2 have resulted in zero apparent porosity. Additives as $AlPO_4$, $GaPO_4$, HfO_2, and Cr_2O_3 were ineffective as sintering aids and produced bars with a porosity of about 20 percent. The best creep rate was for the 5 wt. % Y_2O_3 additive material, while decreasing that value to 2.5 wt. % of Y_2O_3 has obtained the greatest strength value (462 MN/m² or 67 ksi). The oxidation behavior had the highest weight gain value by adding CeO_2, where the material containing ZrO_2 had the lowest oxidation rate. The main problem in this work was the different

additives which had improved different properties of sialon which cannot be accepted in case of using the composite as a solar receiver [14].

Sialon also can be used as a solar selective absorbing coating as applied by Rebouta et al. who have deposited a double absorbing layer of AlSiN/AlSiON on stainless steel using magnetron sputtering technique with different Al:Si ratios. The authors have observed that the best performance of AlSiN and AlSiON layers was at 2.2:1 Al:Si ratio. The formed layers have shown good

solar selective properties, as well as good thermal stability under thermal annealing at 400 °C and 580 °C at air and vacuum, respectively [29].

Wu et al. have prepared β-Sialon/Si_3N_4 composite ceramic for solar heat absorbers from starting materials of α-Si_3N_4, AlN, and Al_2O_3 with additives such as Y_2O_3, La_2O_3, and borax via pressureless sintering approach. The composition of 62.17 % α-Si_3N_4, 28.71 % calcined bauxite, and 9.12 % AlN with sintering at 1580 °C and addition of 3 wt. % of Y_2O_3 and La_2O_3 and no borax, has resulted in firing shrinkage rate of the sample 14.14 %, water absorption 3.16 %, apparent porosity 9.02 %, bulk density 2.85 g·cm^{-3}, and bending strength 193.87 MPa [10].

O- Sialon-Si_3N_4-SiC composite ceramics were prepared by Xu et al. using Si_3N_4 powder, quartz, and different alumina sources as starting materials by non-contact graphite-buried sintering method (Fig. 4), which could greatly lower the sintering temperature of SiC ceramic. The best performance of the composites was at the sintering temperature of 1540 °C, since they had the highest values of bending strength and thermal conductivity which are as high as 66.7 MPa and 10.0 W/mK, respectively. The heat capacity has improved as the working temperature increased and good thermal shock resistance (with a growth rate of 11.0 % after the 30 cycles thermal shock) was possessed. It has been indicated that the good thermal shock resistance enabled the composites to be utilized as thermal storage materials of concentrated solar power generation. However, the low bending strength needs to be improved for such applications [30].

The main properties that control the use of ceramic materials as solar receivers are included in their thermal conductivity, solar absorptance, bending strength, weight gain rate which indicates the oxidation resistance and average heat capacity. The knowledge of these parameters of ceramic materials can decide which material or composite can be used or further enhanced. Table 1 includes the available data of ceramic materials

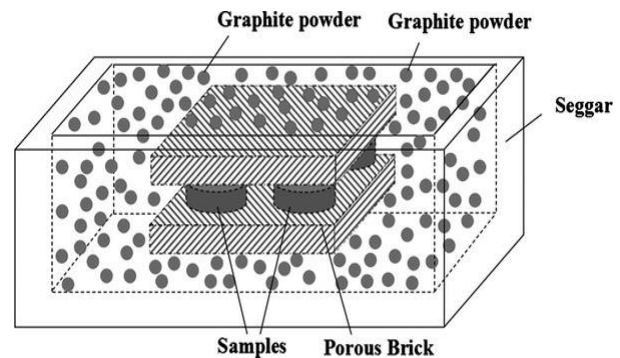and composites that have been studied as a proper solar absorber in solar applications.

Fig. 4 Systematic representation of graphite - buried (noncontact with graphite) sintering (With permission from John Wiley and Sons copyright 2014

5. Conclusions

An overview of the ceramic materials used as solar receivers was introduced. It has been concluded that:

1. In order to indicate the ability of ceramic material to act as a solar absorber, its thermal conductivity, solar absorptance, bending strength, weight gain rate (which indicates the oxidation resistance), and average heat capacity need to be studied.
2. The bending stress is showing an enhanced behaviour by increasing the sintering temperature.
3. Si_3N_4 has more enhanced physical and mechanical properties and high oxidation resistance when combined with oxide materials as Al_2O_3 and MgO.
4. The lack of toughness and reliability of SiC can be improved by adding AlN material. Hence the SiC/AlN composite can be promoted to act as a solar receiver.
5. Si_3N_4/SiC composite is a highly recommended solar receiver ceramic material due to its high thermal conductivity, oxidation resistance, and bending strength. However, the strong covalent bonding that requires high sintering temperature is a weak point of Si_3N_4 material.
6. Sialon composites have been considered as one of the most promising ceramic materials that can be used as solar receivers due to their high temperature resistance, high strength, good thermal shock, and oxidation resistance. All the previous features come along with the low sintering temperature that makes them a more promising candidate than Si_3N_4.
7. According to the hard work conditions of solar receivers, the material that used in such applications is required to have specific and accurate characteristics with further studies. The

available studies aren't sufficient and still many researches can be implied in this field.

8. Future prospect

The present review has shown many applications of sialon composites in the solar receiver field. Based on this review, future work regarding utilization of sialon

References

[1] J. Wu, Y. Zhang, X. Xu, X. Lao, K. Li, and X. Xu, A novel in-situ β-Sialon/Si₃N₄ ceramic used for solar heat absorber, *Ceram. Int.* 41 (2015) 14440–14446, doi: 10.1016/j.ceramint.2015.07.080.

Table 1. Different synthesis methods and raw materials of ceramics applied in solar applications with physical and mechanical properties

Composite	Synth.	Synth. Temp., °C	Raw materials	Thrm. Cond., W/mK	Heat capacity, J/g-K	Solar absorptance, %	Bending strength, MPa	Wt. gain rate, mg/cm²
β-Sialon/Si₃N₄ [1]	†✳	1580	α-Si₃N₄, bauxite, AlN, Y₂O₃, La₂O₃	7.96	0.64	91.1	138.36	0.93 @ 1100°C for 100 h)
O-Sialon/Si₃N₄ [27]	†✳	1600	Si₃N₄, Al₂O₃, Yb₂O₃, Gd₂O₃	-	-	75.16	105.57	17.49 @ 1300 °C for 100 h)
β-Sialon/Si₃N₄ [10]	†✳	1580	α-Si₃N₄, AlN, Al₂O₃, Y₂O₃, La₂O₃, borax	-	-	-	193.87	-
O- Sialon-Si₃N₄-SiC [30]	‡‡	1540	Si₃N₄, quartz, Y₂O₃, different alumina sources	10	0.64	-	66.7	-
Al₂O₃-SiCw [22]	✳✳‡	Not reported	coal series kaolin (CSK) (Shanxi, China), Al, Si	9.36	0.85	-	63.5	-
MgAl₂O₄–Si₃N₄ [20]	†✳	1620	α-Si₃N₄, α-Al₂O₃, MgO	-	-	89.5	248	2.86 @ 1300 °C for 100 h)
MgAl₂O₄-Si₃N₄ [5]	†✳	1620	α-Si₃N₄, α-Al₂O₃, MgO, Sm₂O₃	-	-	92.0	339.4	0.5 @ 1300 °C for 100 h)
Si₃N₄-SiC [24]	†✳	1480	Si₃N₄, SiC, Cr₂O₃, Y₂O₃, ZrO₂	-	-	-	100.26	20-25 @ 1480 °C for 100 h)
SiC-AlN [23]	†✳	2080	AlN, α-SiC, β-SiC, Y₂O₃, Al₂O₃	50.6	-	-	-	-
†✳: Pressureless sintering; ‡‡: noncontact graphite-buried sintering method; ✳✳‡: Aluminium-assisted carbothermal reduction								

materials in solar receivers is recommended to include the following:

(1) Preparation of sialon-based composites by pressureless sintering technique using Si₃N₄, different sources of Al₂O₃, and different rare earth oxides such as Y₂O₃, La₂O₃, and Gd₂O₃.

(2) Different sintering temperatures can be also applied to study its effect on bending strength, oxidation resistance, and mechanical properties of these sialon ceramics.

(3) Controlling the thermal conductivity, solar absorptance and thermal shock resistance of the sialon composites can be considered in future work through the addition of different wt.% of rare earth oxides, Si₃N₄, and Al₂O₃.

[2] H. L. Zhang, J. Baeyens, J. Degrève, and G. Cacères, Concentrated solar power plants: Review and design methodology, *Renew. Sustain. Energy Rev.* 22 (2013) 466–481, doi: 10.1016/j.rser.2013.01.032.

[3] S. Mahavara, M. S. Khan, and T. Yadav, Synthesis, characterization and testing of black metal oxide nanoparticles as solar concentrator receiver material, *Mater. Today Proc.* 8 (2019) 22–27, doi: 10.1016/j.matpr.2019.02.076.

[4] A. G. Konstandopoulos, C. Pagkoura, and S. Lorentzou, Concentrating solar power technology Principles, developments and applications. New Delhi: Woodhead Publishing Limited, 2012.

[5] Y. Zhang, J. Wu, X. Xu, Y. Zhou, Q. Zhang, and J. Song, Effect of Sm₂O₃ on microstructure and high-

temperature stability of $MgAl_2O_4$-Si_3N_4 ceramic for solar thermal absorber, *J. Alloys Compd.* 711 (2017) 365–373, doi: 10.1016/j.jallcom.2017.04.018.

[6] S. E. Division. Review of sputter deposited mid- to high- temperature solar selective coatings for flat plate/evacuated tube collectors and solar thermal power generation applications.1–86, 2010.

[7] A. A. Kudirka and R. H. Smoak, Ceramic technology for solar thermal receivers, *Am. Soc. Mech. Eng.* 1(1981).

[8] C. K. Ho, Advances in central receivers for concentrating solar applications, *Sol. Energy.* 152 (2017) 38–56, doi: 10.1016/j.solener.2017.03.048.

[9] M. Ali, M. Rady, M. A. A. Attia, and E. M. M. Ewais, Consistent coupled optical and thermal analysis of volumetric solar receivers with honeycomb absorbers, *Renew. Energy.* 145 (2020) 1849–1861, doi: 10.1016/j.renene.2019.07.082.

[10] J. F. Wu, Y. X. Zhang, X. H. Xu, D. Z. He, Y. Zhou, and Y. Liu, Preparation and performance of β-sialon/Si_3N_4 composite ceramics for solar heat absorber, *Appl. Mech. Mater.* 692 (2014) 234–239, doi: 10.4028/www.scientific.net/AMM.692.234.

[11] O. Guillon, Advanced ceramics for energy conversion and storage, India: Matthew Deans, 2020.

[12] D. G. Morris, A. López-Delgado, I. Padilla, and M. A. Muñoz-Morris, Selection of high temperature materials for concentrated solar power systems: Property maps and experiments, *Sol. Energy.* 112(2015) 246–258, doi: 10.1016/j.solener.2014.09.050.

[13] V. J. Tennery and G. W. Weber, An assessment of materials for use in a solar ceramic receiver for chemical process heat, *OAK RIDGE Natl. Lab.*, 1979.

[14] R. L. Ashbrook, Improved performance of silicon nitride-based high temperature ceramics, 1977.

[15] D. P. H. Hasselman, J. P. Singh, and K. Satyamurthy, Identification and analysis of factors affecting thermal shock resistance of ceramic materials in solar receivers, 1980.

[16] D. H. A. Besisa, E. M. M. Ewais, E. A. Mohamed, N. H. A. Besisa, and Y. M. Z. Ahmed, Inspection of thermal stress parameters of high temperature ceramics and energy absorber materials, *Sol. Energy Mater. Sol. Cells.* 203 (2019) 110160, doi: 10.1016/j.solmat.2019.110160.

[17] M. Bengisu, Engineering Ceramics. New York: Springer, 2001.

[18] W. T. Bakker and D. Kotchick, Development of ceramic heat exchangers for indirect fired gas turbines, *Proc. ASME Turbo Expo.* 5 (1982), doi: 10.1115/82GT182.

[19] X. Xu, Z. Rao, J. Wu, Y. Li, Y. Zhang, and X. Lao, In-situ synthesis and thermal shock resistance of cordierite/silicon carbide composites used for solar absorber coating, *Sol. Energy Mater. Sol. Cells.* 130 (2014) 257–263, doi: 10.1016/j.solmat.2014.07.017.

[20] J. Wu, Y. Zhang, X. Xu, T. Deng, X. Lao, K. Li, and X. Xu, Thermal shock resistance and oxidation behavior of in-situ synthesized $MgAl_2O_4$-Si_3N_4 composites used for solar heat absorber, *Ceram. Int.* 42 (2016) 10175–10183, doi: 10.1016/j.ceramint.2016.03.133.

[21] C. Wang, H. Wang, X. Fan, J. Zhou, H. Xia, and J. Fan, Fabrication of dense β-Si_3N_4-based ceramic coating on porous Si_3N_4 ceramic. *J. Eur. Ceram. Soc.* 35 (2015) 1743–1750, doi: 10.1016/j.jeurceramsoc.2014.10.015.

[22] X. Lao, X. Xu, J. Wu, X. Xu, Y. Zhang, and K. Li, Effect of silicon on properties of Al_2O_3-SiC_w composite ceramics in-situ synthesized by aluminium-assisted carbothermal reduction of coal series kaolin for solar thermal storage, *J. Alloys Compd.* 692 (2017) 825–832, doi: 10.1016/j.jallcom.2016.09.107.

[23] D. H. A. Besisa, E. M. M. Ewais, Y. M. Z. Ahmed, F. I. Elhosiny, D. V. Kuznetsov, and T. Fend, Densification and characterization of SiC-AlN composites for solar energy applications, *Renew. Energy.* 129 (2018) 201–213, doi: 10.1016/j.renene.2018.05.100.

[24] M. Liu, X. Xu, J. Wu, G. Xu, G. Xue, and J. Liu, Modification of Si_3N_4-SIC heat absorption ceramic material using for tower type solar thermal power plant, J.S. Carpenter, C. Bai, J.g Hwang, S. Ikhmayies, B. Li, S. N. Monteiro, Z. Peng, and M. Zhang (ed.), Characterization of Minerals, Metals, and Materials 2014. (2014), doi: 10.1002/9781118888056.ch6.

[25] K. Liddell and D. P. Thompson, The future for multicomponent SiAlON ceramics, *Key Eng. Mater.* 237 (2003) 1–10, doi: 10.4028/www.scientific.net/kem.237.1.

[26] J. Luo, C. Xi, Y. Gu, L. Zhang, C. Zhang, Y. Xue,

and R. Liu, Superplastic forging for sialon-based nanocomposite at ultralow temperature in the electric field, *Sci. Rep.* 9 (2019) 1–6, doi: 10.1038/s41598-019-38830-1.

[27] J. Wu, C. Ding, X. Xu, and K. Mi, Effects of Gd_2O_3 and Yb_2O_3 on the microstructure and performances of O'-Sialon/Si_3N_4 ceramics for concentrated solar power, *Ceram. Int.* (2020), doi: 10.1016/j.ceramint.2020.10.083.

[28] K. M. Reddy and B. P. Saha, Effect of porosity on the structure and properties of β-SiAlON ceramics, *J. Alloys Compd.* 779 (2019) 590–598, doi: 10.1016/j.jallcom.2018.11.277.

[29] L. Reboutaa, A. Sousaa, M. Andritschkya, F. Cerqueiraa, C.J. Tavaresa, P. Santillib, K. Pischow, Solar selective absorbing coatings based on AlSiN/AlSiON/$AlSiO_y$ layers, *Appl. Surf. Sci.* 356 (2015) 203–212, doi: 10.1016/j.apsusc.2015.07.193.

[30] X. Xu, X. Lao, J. Wu, Z. Rao, Y. Zhou, D. He, and Y. Liu, Preparation and performance study of sialon-Si_3N_4-sic composite ceramics for concentrated solar power, *Int. J. Appl. Ceram. Technol.* 12 (2015) 949–956, doi: 10.1111/ijac.12374.