Sialon from synthesis to applications: an overview

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Abstract

Sialons are the spotlight of current investigation as low-cost and outstanding alternatives to the currently used metal alloys in various applications. The excellent high-temperature properties, high mechanical properties, structural reliability, good sinterability, easy densification with its low-cost processing make them superior candidates in many applications such as automotive engines, high-performance bearings, wear components, and gas turbine blades. In addition, the existence of two interstitial crystallographic sites in their crystal structure gives the opportunity to accommodate some rare earth element activators such as Eu$^{2+}$, Yb$^{3+}$, Ce$^{3+}$, and Pr$^{3+}$. These types of sialon-based materials have recently found a new promising application as a luminescent material for white light-emitting diodes. The aim of this review is to survey and provide a comprehensive look at the most relevant and significant publications regarding the development of sialons and their processing into both structural and luminescent materials. Such information forms a database that could enable scholars and engineers to tailor a final product derived from sialons with specific characteristics for a certain application. This review article should be of concern to engineers and scientists interested in the development and utilization of sialons for structural and wLEDs applications.

1. Introduction

Alumino-silicate oxynitrides (sialons) are solid solutions of Al$_2$O$_3$ and Si$_3$N$_4$. There are two main representative members for sialon materials, β- and α-phases. The former is the low-temperature phase that has elongated grains and exhibits good thermal conductivity and high fracture toughness but relatively low hardness [1]. The latter is the high-temperature phase that reveals equiaxed grains with good wear resistance and high hardness but low fracture toughness and thermal conductivity. In general, sialon ceramics are superior hard materials with comparable or even better high-temperature properties than silicon nitride ceramics. In addition, the other properties of sialon are comparable with that of silicon nitride ceramic from mechanical, thermal, and electrical points of view (as shown in Table 1). Nevertheless, they have better sinterability and offer advantages of low-cost fabrication and easier densification compared to silicon nitride ceramics. Moreover, the machining of sialon-based ceramics into complex industrial components is cost-effective and much easier compared to the machining of silicon nitride ceramics. Accordingly, sialon-based ceramics are the spotlight of current investigations as low-cost and outstanding alternatives to the currently used silicon nitride ceramics and metal alloys for several harsh-environment industrial applications. On the other hand, rare-earth (Re) doped sialon materials have recently attracted considerable attention as good phosphors for wLEDs application due to the multiple characteristics provided by sialon host materials over the conventional oxide-based host materials. These characteristics originated from the rigid structure of sialon hosts and the covalent bonding nature between the activators (rare-earth element) with the ligands in sialon host [2]. Accordingly, this review article provides an overview for the most relevant and significant publications regarding development of sialon-based materials and their processing into structural and luminescent materials. Information reported about the crystal structure, properties, and synthesis of different sialon phases and their respective applications have been reviewed and discussed.
2. Definition, types, polymorphism, crystal structure, and synthesis of sialons

2.1. Definition

Alumino-silicate oxynitrides (sialons) are solid solutions of Al₂O₃ and Si₃N₄, which are typically formed by partial substitution of Si-N bonds by Al-O bonds in a Si₃N₄ hexagonal crystal structure. There are four representative members for sialon materials, β-, α-, X-, and O-phases.

2.2. Polymorphs of sialons

2.2.1. β-Sialon

β-sialon is the low-temperature phase that has reinforced microstructure of elongated grains (aspect ratio of 4–7) with high fracture toughness (~ 7–8 MPa m⁰.₅) [3,4], superb strength (700–1100 MPa), and good thermal conductivity (13.5–19.7 W/mK) but relatively low Vickers hardness (~ 1500–1700 kg/mm²) and thermal shock resistance [1]. β-sialon is the most extensively utilized sialon structure, and it usually forms by substituting up to two-thirds of the Si in the β-Si₃N₄ hexagonal crystal structure by Al while the replacement of an equivalent concentration of N by O maintains the valency compensation. These replacements give rise to a range of β-sialons, Siₙ₋ₓAlₓOₓN₄₋ₓ, with 0 < x < 4. Several reports describe the synthesis of β-sialon powder from kaolinite [5], SiO₂-Al₂O₃-H₂O powder [6], SiO₂-Al₂O₃ powder [7], an alkoxide-derived SiO₂-Al₂O₃ co-precipitate [8], and SiO₂-Al₂O₃ gels [9], all heated in the presence of carbon under flowing N₂ gas. Oyama and Kamigaito [10] reported that a composite of β-Si₃N₄ and β-sialon was successfully manufactured starting from different powder mixtures of β-Si₃N₄, α-Al₂O₃, and Li₂CO₃ powders using hot pressing (1700 °C, 20 min, 30 MPa). The synthesized β-sialon revealed the same crystal structure of β-Si₃N₄; however, its lattice parameters were shifted toward lower 2-theta by an amount proportional to the oxide content. Following that, β-sialon single-phase composition was efficiently prepared by hot pressing method of (1-x) Si₃N₄ + xAl₂O₃-AlN system, where x = up to 0.8 [11].

Gunchenko et al. [12] have made up single-phase β-sialon sintered ceramics with optimum physicochemical and mechanical properties using solid-state process starting from powder mixtures prepared from Si₃N₄-AlN-Al₂O₃ system with compositions of Si₆₋ₓAlₓO₂₋ₓN₄₋ₓ (Z = 0–4.2). In [13], crystal structure and lattice parameters of the four β-sialons synthesized using self-sustained high-temperature synthesis were precisely studied using a neutron diffractometer; the results of neutron diffraction patterns agreed well with the model structure of β-Si₃N₄ material with unit cell values in the range of a = 0.76072–0.77004 nm and c = 0.29274–0.30003 nm based on the value of Z = 1–4, matching with P63 space group. Early studies on resistance of two β-sialon materials to oxidation in the temperature range of 800–1300 °C showed that residual β-Si₃N₄ as well as a glassy phase affects negatively on oxidation resistance of β-sialons, and the oxidation of sialons is a diffusion limited process [14]. In another study, it was shown that the optimal characteristics of β-sialon ceramics were displayed by a single-phase structure; this study also verified that mechanical properties of β-sialon ceramics are highly dependent on their structure, phase composition, and the existence of the intergranular glassy phase. β-Sialon ceramics prepared by slip casting process in reference [15] demonstrated about 600 MPa bending strength, 4.1 MPa.m⁰.₅ fracture toughness for Z = 0.5 to 1; and the mechanical properties have significantly degraded for Z values within the range from 2 to 4.

β-Sialon-based ceramics have recently received an increasing attention from materials scientific community for radomes utilized for high-speed missile applications. β-Sialon-based ceramics with a wide-range composition (Si₆₋ₓAlₓO₂₋ₓN₄₋ₓ; Z = 0–4.1) provide identical characteristics to the typical radome materials (fused silica, Si₃N₄, Si₃N₄/BAS and Si₃N₂O) (see Table 1), together with their high capability to be sintered in the full-dense structure using pressureless sintering preserving the near-net-shaped radome structure [16–20]. Conversely, Si₃N₄ and Si₃N₄/BAS display poor sinterability and their densification using pressureless sintering is impossible without using huge amount of certain sintering aids that deteriorate their characteristics and lead to structure failure. Therefore, the latter materials are generally densified using hot isostatic pressing that disturbs and destroys the near-net-shaped radome structure. In addition, fused silica is the ideal material for radome applications; however, its inferior strength (40–50 MPa) and limited temperature withstanding capability (>800 °C) restrict its use for only certain low-speed radome applications. Besides, synthesis of Si₃N₂O with consistent properties is not an easy task because it is typically synthesized via calcination of α-Si₃N₄ in atmospheric air; this reaction is quite sensitive to humidity, powder particle size, and temperature fluctuation of the furnace. In this sense, β-sialon-based ceramics are still the superb materials that can be easily consolidated into the near-net-shape radome structure for high-speed missile applications. Photograph of β-Si₆Al₃O₂N₆ proto-type

| Table 1. Radome materials and their main properties [16]. |
|----------------------|------------------|-------------------|----------------|------------------|
| Material property    | Fused silica     | β-Sialon          | Si₃N₄    | Si₃N₄/BAS         | Si₃N₂O          |
| Temp. cap. (°C)      | >800             | <1300             | <1300    | <1300             | <1300            |
| Dielectric const (10⁴) | 4.01             | 7.34              | 8.59     | 8.16              | 5.02             |
| Loss tangent (10³ °C) | >0.01            | 0.003             | 0.013    | -                 | 0.0025           |
radome structure sintered by pressureless sintering process at 1675 °C for 4 h under N₂ atm is shown in Figure 1.

### 2.2.2. α-Sialon

On the other hand, high-temperature α-phase reveals equiaxed microstructure with good wear resistance and high Vickers hardness (1900–2100 kg/mm²), but low fracture toughness (3–4 MPa m⁰.⁵), flexural strength (350–500 MPa), and thermal conductivity (8.16–8.22 W/mK). α-Sialon is synthesized by the addition of Al₂O₃ into α-Si₃N₄ with small amounts of yttria or rare-earth oxides. Numerous reports have shown that α-sialon powders can be prepared by heating carbon-containing powder mixtures of SiO₂-Al₂O₃-CaCO₃ [21], SiO₂-Al₂O₃-metal (Ca or Y) [22,23], clay metal compounds [24], and talc (Mg₃Si₄O₁₀(OH)₂) halloysite clay minerals [25,26]. α-Sialon has the general formula MₙSi₁₂₋₂ₙAl₃₋ₓOₓN₁₆₋ₙ, where M is the metal cation present in the sintering aid, which is used as a stabilizer of α-phase structure that can transform at high temperatures into β-phase in the presence of liquid-phase oxynitride glass [1], which forms typically at the grain boundaries due to reaction of alumina and sintering aids with SiO₂ formed on the Si₃N₄ powder surface [27]. Sintering aids used for α-phase stabilization are typically oxides of Li, Ca, Mg, Y [28] and most rare earths such as Nd, Sm [29], Dy, and Yb [30] (excluding La, Pr, Ce, and Eu), x = n divided by the valency of the M cation. The metal cations present in the sintering aid mainly control the stability of α-phase; hence, selecting a sintering aid material is related to the capability to stabilize the sintering aid. Solubility limit of stabilizing cations in α-sialons and also thermal stability of the latter materials increase with the decrease of the cation radius following the sequence of Nd ≈ Sm > Y > Yb. According to this study, M-α-sialon ceramics (M = Nd, Sm, Y, Yb) were heated at 1250 °C for 20 h; Yb-doped-α-sialons showed the best oxidation behavior, and different stabilizing cations were found to have a negligible effect on mechanical properties of α-sialon ceramics.

### 2.2.3. X-sialon and O-sialon

X-phase has a similar crystal structure to that of mullite where columns of octahedral Al₂O₆ are bridged by tetrahedral AlO₄ and SiO₄ units, and it varies stoichiometrically from SiAlON to Si₁₆₋₃Al₂₂₋₃O₄₈₋₃N₁₁₋₃ [31]. Hot-pressed X-sialon composites containing 28 vol.% Al₂O₃ platelets demonstrated 3.18 g/cm³ bulk density, 4.16 MPa m⁰.⁵ fracture toughness, and 1270 kg/mm² hardness [32]. O-sialons, on the other hand, have stoichiometric composition of Siₓ₋₄AlₓNₓ₋₄Oₓ, where 0.04 ≤ x ≤ 0.4, and they belong to the orthorhombic space group (PCTC21) with lattice parameters varying based on the prepared composition: a = 0.88807(13) – 0.89254(5) nm, b = 0.54965(4) – 0.54988(7) nm, and c = 0.48550(6) – 0.48596(2) nm. The latter phase exhibits the highest oxidation resistance among all sialon phases; more importantly, low-dense O-sialon ceramics are typically applied as electromagnetic transparent materials due to their light weight, low dielectric constant, and dielectric loss [33]. More information about the physicochemical properties of O-sialons can be found in reference [34].

### 2.3. Crystal structure of α- and β-sialons

According to a study of the literature, the two sialon polymorphs have a hexagonal structure with (Si,Al)(O,N)₄ tetrahedra of different orientation along the C axis. α-Sialons have the same α-Si₃N₄ structure that is built upon [(Si, A1)(N, O)₄] tetrahedra, and the modifying cations are partially accommodated in the interstitial positions in the (Si, Al)-(N, O) network [35] (Figure 2). Each (A1, Si) atom in α-structure is tetrahedrally coordinated by (O, N) atoms, and every (N, O) atom has three (A1, Si) atoms as closest neighbors. Each modifying cation is bound to seven (N/O) atoms, and the average M-(N, O) bond lengths are almost the same, about ~0.26 nm, when M = Y or Ca. The (Si, A1)-(N, O) bond lengths lie between 0.17 and 0.18 nm with a mean at 0.176 nm, which is a bit larger than the average Si-N bond length in α-Si₃N₄ (0.174 nm). The pretty small difference in the bond length values among Si₃N₄ and sialons proposes that Al and O atoms do not separate appreciably in any of the Si and N sites, respectively. Besides, the cell volume of α-sialons is always a bit greater than that of α-Si₃N₄ due to the replacement of a small number of Si-N bonds by A1-N bonds [36]. In the meanwhile, the proposed crystal structure of MₓSi₅AlOₓN₁ₓ β-sialon is shown in Figure 3 [37]. β-Sialon is a framework of corner-sharing (Si,Al)(O,N)₄ tetrahedra.
2.4. Sialon properties dependence on its microstructure and phase composition

So far, the vast majority of commercially available sialons is the β-phase [38]. In β-sialons, lower viscosities of oxynitride glass formed occasionally during its sintering of β-sialons allows easier densification but deteriorate its mechanical and chemical properties at high temperatures [1], reducing high-temperature strength and creep resistance. This consequently limits the practical maximum operating temperature of β-sialon ceramics to approximately 1000 °C. In comparable, the cations of sintering aids used to stabilize α-structure is often interstitially incorporated into the solid solution, leading to reducing volume of intergranular glassy phase [1]. Besides, oxynitride glasses with improved creep resistance and higher viscosity are formed by rare-earth cations with small ionic radii such as Dy, Er, Lu, and Ho [27]. Accordingly, the mechanical properties of α-sialons at elevated temperatures retain better, and correspondingly the maximum operating temperature of these compounds is high (up to 1400 °C). Further, improving the fracture toughness and flexural strength of α-sialon could be achieved by producing a bimodal equiaxed-acicular microstructure by using elongated seed crystals in the starting powder or carefully selecting the starting composition and control the sintering conditions [39,40]. Ultimately, α-sialon materials can be applied in corrosive environments and for applications requiring high temperature and strength since they retain desirable properties at elevated temperatures such as hardness, creep resistance, strength, corrosion and oxidation resistance, wear resistance, thermal expansion with low coefficient, and good thermal shock resistance. On the other hand, the thermal conductivity of single-phase β-sialon was found to have a range from 13.5 to 19.7 W/mK. These values decline linearly with rising α-sialon content in the double-phase sialon composite. This decline follows the following equation: \( K = 12.46 - 0.0434 \ f \). This equation only applied for double-phase sialon composite, where \( f \) is wt.% of α-sialon phase; \( K \) is the thermal conductivity of the double-phase composite. The thermal conductivity (K) value of the single-phase α-sialon is typically ~8.16 W/mK, which is almost half that of β-sialon phase. The low K value of α-sialons can be primarily ascribed to the high degree of defects and lattice asymmetry of the latter sialons caused by incorporation of stabilizing cation and further substitution of Al-O bonds by Si-N ones. This in turn makes a significant decline in the mean free path length of the phonons and result in reducing the K value of α-sialon compared to that of β-polymorph [38].

2.5. Disadvantages of sialons

Currently, sialons are one of the most important advanced structural materials since they have a good combination of properties including high dimensional stability, high-strength at elevated temperatures, good wear and corrosion resistance, low weight density, high hardness, good resistance to thermal shock resistance, and high elastic modulus. In spite of that, they suffer indelibly from defects of a rather weak fracture toughness (3–8 MPa m\(^{1/2}\)) [1,41–43]. Because of their low fracture toughness, reliability of sialons is not yet adapted to production commitment. Several
techniques have been developed and many challenges have been overcome to manufacture strengthened and toughened sialon-based products. These techniques included fabrication of α/β-sialon composites [41,44–47], fiber-reinforced sialons using high quality carbon fiber and/or SiC fiber [48–52], particle whisker-reinforced sialons [53]. The best method to enhance the fracture toughness of sialons was the preparation of a sialon matrix composite using a reinforcement material. Sialon-reinforced composites exhibited improved toughness with better reliability, reduced crack propagation, and even more resistance to failure.

2.6. Synthesis of sialon-based phosphors

2.6.1. Solid state reaction

The solid-state reaction method is applied by mixing and blending of activators, host crystal with high-purity materials, and fluxes. The mixture is then fired under an appropriate atmosphere. Afterward, the fired mixture is crushed, milled, and sieved to remove the excessive crushed and large particles. The surface of the product might undergo treatments in some cases. Reactants used for the synthesis of sialons by the solid-state process included carbonates (e.g. CaCO3, Li2CO3), oxides (e.g. Al2O3, Y2O3), nitrates (e.g. Si3N4, AlN), metals (e.g. Al, Si), and carbides (e.g. SiC) [54–66]. Among the synthetic methods used for sialon production, the solid-state method is the most suitable and cost-effective approach for mass-producing sialon powders at large scale. This method was also found to be the most adequate technique for producing near-net shaped sialon-based ceramics with high mechanical properties [54]. On the other side, the main drawbacks of this process are related to the formation of coarse particles with low surface area, the inhomogeneity of the product, and the appearance of some defects that are harmful to luminescence [67]. The use of solid-state method for the synthesis of sialon in an atmosphere of N2 or N2/H2 mixture requires extreme temperature conditions, sometimes exceeding the thermal stability limit of nitrates. This synthesis method is a multistep process, which is limited by many flaws such as long synthesis time, high sintering temperatures, and contamination of the final product during pulverization of the strong sintered briquettes.

2.6.2. Microwave synthesis method

The microwave synthesis method is depending on the quick and uniform heating over the whole sample since the energy of the microwave is absorbed immediately by the sample. There are two microwave apparatus available: the conventional microwave oven that has a multimode microwave such as the ceramics-sintering furnaces and domestic microwave ovens, and the other apparatus is the custom-tailored one that has a single-mode microwave and its energy focused to a small area. Reactants used for preparation of sialon-based materials by microwave technique include (Clay-carbon-Nitrogen Montmorillonite), (Boehmite-silica-SiC-carbon-Nitrogen) and (Si3N4 + Al2O3 [68]). Microwave synthesis of ceramic materials is an easy, facile technique for processing broad range of new ceramic materials of wide applications for the future. The advantage of the microwave heating techniques is represented in the saving of energy and the short time of processing, which reduce the manufacturing cost. Microwave synthesis requires short sintering time because the microwave heat is deposited in the sample core; that is why shorter time is demanded to sinter the entire sample than would be demanded to diffuse the energy from the exterior. In addition, a specific component in the mixture can be heated, and hence, the microwave method can develop a new synthetic material [56]. That is why, the prospective advantages of microwave approach over conventional solid-state methods for ceramic materials processing include more-uniform heating, high product yield and uniformity, unique or enhanced texture and microstructure, better characteristics of the product, greater energy efficiency, large-scale production using smaller plant size, and the capability to prepare new functional materials. What is more important, the rapid sintering process leads to final product with smaller particle size and enhanced mechanical properties. In spite of the advantageous application of microwave synthesis in ceramic sintering, the perceived output of this technology has not been largely realized at the production scale.

2.6.3. Combustion method

Combustion process or self-propagating high-temperature synthesis (SHS) is a wet-chemical synthesis method in which repeated heating and further calcinations of materials are not required. This method is an exothermic reaction that occurs by evolution of light and heat, which leads to crystallization and formation of phosphor materials. This method is time-saving and energy-efficient process for synthesizing various industrial ceramic materials. It is a self-sustaining process that exploits the heat evolved from the continuous exothermic reaction. That is why, no external energy or heat is demanded, apart from the ignition energy. This combustion technique required a mixture of fuel and oxidizers that ignited to start the combustion [56]. This method is a good alternative to the conventional sintering methods, owing to its potential advantages including (1) short sintering time, (2) high purity of the final sialon products, (3) simplicity of the procedure, and (4) low-energy consumption. For the SHS to be self-sustaining, the combustion process should be associated with
high-temperature exothermic reaction with adiabatic temperature $T_{ad} \geq 1800$. $T_{ad}$ is a thermodynamic parameter that expresses the product temperature under adiabatic conditions as a result of the heat evolution from the reaction. $T_{ad}$ is calculated by the following equation: $\sum n_i C_{pi} dT = -\Delta H_r^\circ$, where $n_i$ is the number of moles of the product ($i$), $C_{pi}$ expresses the specific heat capacity of the product ($i$), and $\Delta H_r^\circ$ denotes the reaction enthalpy. Actually, the adiabatic temperature is commonly higher than the combustion temperature because of the heat losses that occurred during the combustion process to the surroundings. $T_{ad}$ gives a good estimate to the reaction temperature, and it gives an indication whether or not combustion process can continue via the self-propagating regime [69–75]. Reactants utilized for the synthesis of siloxons by the combustion process included Si, Al, SiO$_2$, SiI$_n$Na, AlN, Y$_2$O$_3$, kaolin, Al dross, CaCO$_3$, CaO, MgCO$_3$, and SrCO$_3$ [76–86].

### 2.6.4. Gas reduction and nitridation

Nitride and oxynitride phosphors can be synthesized with gas reduction and nitridation (GRN) process, which is a cheap and an effective method that involves commercially available oxides as the starting powders. The reaction of this method is proceeding in an alumina or quartz tube furnace and with NH$_3/\text{CH}_4$ or NH$_3$ gas flows, which acts as nitriding and reducing agents. There are many parameters that control the purity of nitride phosphors phase after the GRN reaction, such as the firing temperature, gas flowing rate, heating rate, holding time, and post-annealing. Hence, controlling these processing parameters can produce highly efficient phosphors with a narrow particle size distribution and small particle size (1 ~ 2 μm) [57].

### 2.6.5. Carbothermal reduction and nitridation

Carbothermal reduction and nitridation (CRN) process has been used extensively to produce nitride ceramic powders, including aluminum nitride, silicon nitride, and β-silicon. Such a method was also used to produce multinary nitride and oxynitride luminescent materials, such as Ca-α-silicon: Eu$^2$. Synthesis of Ca-α-silicon: Eu$^{2+}$ includes reactants as Al$_2$O$_3$, SiI$_n$Na, CaCO$_3$, Eu$_2$O$_3$, and carbon (graphite), and the purity of the phase is depending on the firing temperature, holding time, heating rate, post-annealing, and the starting composition (e.g. carbon/oxides ratio). The stoichiometric excess of carbon has a role in the success of the CRN process since it can enhance the dispersion of the powder, raise the reaction rate, manage the aggregation of the powder, and allow the transformation to complete easily. The rate-determining step in the CRN process includes the solid-solid reaction between oxides and carbon, and the rate-controlling mechanism includes the availability of carbon. It is important to remove the excess carbon in the prepared nitride phosphors after CRN process because it reduces the luminescence and absorption of the phosphor powder itself. One of the common ways to remove carbon is firing the powder at temperatures above 600 °C in an oxidizing atmosphere. However, the oxidation of phosphor powders that occurred by this method decreases the phosphors luminescence. Another method to remove residual carbon is the annealing of the phosphor powders at high temperature in a carbon-free furnace and under NH$_3$ or N$_2$ atmosphere [57]. CRN process has many disadvantages; for example, it may cause concurrent formation of SiC and contamination of carbon [67, 87]. In addition, the precise control of the product phase composition is difficult because the process is associated with the emissions of greenhouse gas CO$_2(\text{g})$ and CO$_3(\text{g})$, which have different partial pressures. Furthermore, the large linear shrinkage complicates the control of the product dimension and shape. Hence, the products from CRN process are generally very fragile, and as a result, their compaction is very low.

### 2.6.6. Aluminothemic nitridation reaction

Aluminothemic nitridation reaction (ARN) process can be achieved by wet blending and calcining of the calculated amounts of aluminosilicate and Al under N$_2$ gas flow. The equations that explain the reactions are as follows:

$$\text{Al}_i(\text{s}) \rightarrow \text{Al}_j(\text{l}) \quad [1]$$

$$\text{Si}_{\text{im}}\text{Al}_n\text{O}_{j+i}[\text{Dehydrated mineral}] + 4x \text{ Al} \rightarrow 3x \text{ Si} + 2x \text{ Al}_2\text{O}_3 + \text{Si}_{\text{im}} - 3x\text{Al}_n\text{O}_{j-i-6x}[\text{Phase A}] \quad [2]$$

$$3\text{SiO}_2 + 4\text{Al} \rightarrow 3\text{Si} + 2\text{Al}_2\text{O}_3 \quad [3]$$

$$\text{Al}_j(\text{l}) + \frac{1}{2}\text{N}_2 \rightarrow \text{AlN}_i(\text{s}) \quad [4]$$

$$x\text{Si} + b\text{AlN} + c\text{Al}_2\text{O}_3 + d\text{N}_2 \rightarrow [\text{Si} - \text{Al} - \text{O} - \text{N}] \quad [5]$$

$$\text{t} - \text{Al}_2\text{O}_3[\text{Transition alumina phases}] \rightarrow a - \text{Al}_2\text{O}_3 \quad [6]$$

First, aluminum melts according to Eq. [1]; thereafter, Eqs. [2, 3 & 4] is a generalization of the reaction, where $m$, $n$, $l$, and $x$ are stoichiometric coefficients, as well as “A” is a mixture of oxygenated products, which is totally different from the dehydrated phase [88]. Nitrogenous phases (Si-Al-O-N) and α-Al$_2$O$_3$ are formed by the reaction of aluminum nitride, transition alumina, and silicon according to the simplified Eq. [5& 6]. The aluminothemic reduction and nitridation process is a preferable choice to obtain high pure sialon, in which the reducing agent used in the process is aluminum, which is reactive much more than C or SiC (that used in CRN) and can be cost-effectively extracted from many waste resources such as coal fly ash [89] and aluminum dross [88]. Compared to carbon coke or
carbon black, aluminum is more expensive, but the free-carbon removal process and the release of heat in the nitridation process of aluminum make it more attractive to synthesize sialon composites [90]. Different starting materials used in the preparation of different types of sialons via various synthesis methods together with the most important results were concluded in Table 2 [7,15,45–191]. Such information could be used as a database for the material scientists who are interested in dealing with sialon-based materials.

3. Applications of sialons

3.1. Structural applications

3.1.1. Limitations of metal alloys

Nowadays, the demands for materials that can work in more aggressive environments than ever before with stronger, harder, more heat- and wear resistant features and with reasonable cost, have been escalating in various industries. For example, current aircraft engines require increasing the ratios of thrust-to-weight, which is normally accomplished by both weight lessening and turbine inlet temperatures enhancement, where the required operating temperatures of modern jet engines exceed the temperature limitations imposed by metallic turbine components. Besides, the reduction of energy consumption and the greenhouse gas emissions are the greatest challenges for the transport sector over the next decades. In this context, it has therefore become essential to seek for super-hard light-weight inert materials as alternatives to the currently available metal alloys. In fact, non-oxide engineering ceramics (like silicon nitride ceramics) have recently attracted the attention, and they have become accepted in some industries.

3.1.2. Si3N4 ceramics and their limitations

Silicon nitride (Si3N4) is a superior non-oxide engineering ceramic that reveals extreme strength and toughness at elevated temperatures. Early orientation to Si3N4 for high-temperature structural applications is related to its covalently bonded structure and the adamantine characteristic of two electrons per Si-N bond. These bonds with their 3-D linked network gave rise to materials with outstanding thermal shock resistance, superb hardness, high Young’s modulus, and excellent refractoriness in addition to a relatively low weight of the final product [192]. Si3N4 material is twice as hard as tool steel and 60% less in weight than steel. It does not deteriorate at high temperatures due to its superior thermal shock resistance and good resistance to creep, wear as well as oxidation. Accordingly, it has been widely used in the applications that require a unique material with elevated strength, high fracture toughness, and low wear properties such as automotive engines, gas turbine blades, high-performance bearings, and glow plugs [193–197] (Figure 4).

Nevertheless, some disadvantages of silicon nitride ceramics deteriorate their market expansion and motivate the search for alternatives. One of these disadvantages is the superplastic machining of the silicon nitride ceramics into complex-shaped components. This process is time-consuming and cost-ineffective because of the low strain rate (10−4 S−1) and high superplastic deformation temperature (1600°C) of the silicon nitride ceramics [198]. In addition, the poor sinterability of the silicon nitride makes its densification an energy consuming process that requires harsh temperature conditions (1700–1900°C) and huge amounts of sintering additives, such as rare earth oxides or yttria [199, 200]. These additives, on the other hand, react with part of the nitride itself forming M-SiO-N liquid phase (M is yttrium or rare-earth metal), which solidifies into a glass at the grain boundaries. This glassy grain-boundary phase significantly affects the developed silicon nitride-based ceramics as it deteriorates its high-temperature mechanical and chemical properties. As a result, subcritical crack growth, creep, oxidation, and other lifetime-determining properties are significantly affected, which is leading to accelerate the material destruction [201] (see Figure 5).

3.1.3. How to solve the limitations of Si3N4 ceramics

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 Si3N4 hexagonal crystal structure forming solid solutions of Al2O3 and Si3N4 that are so-called alumina-silicate oxynitrides (sialons). Beside 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 appearance of alumina in the starting mixture facilitates formation of Si-Al-O-N liquid phase having lower viscosity, which eventually enhances material densification [192]. 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) make their machining into complex shape much easier and cost-effective [198]. These advantages of sialon-based ceramics with the fact of its structure reliability and stability under harsh environmental conditions make them outstanding alternatives to the currently used silicon nitride ceramics in various industrial applications.
### Table 2. Different starting materials used in sialon preparation via various synthesis methods.

| Starting materials | Parameters studied | Important results | Synth. proc. |
|--------------------|--------------------|--------------------|--------------|
| Si₃N₄ + AlN + Al₂O₃ | [54] Effect of sintering technique (t, ℃ and) | Pressure-less sintering process of fine-grained starting materials was found to be the most suitable technique for production of near-net-shape β-sialon ceramics with high mechanical properties | ↓ |
| Si₃N₄ + AlN + Al₂O₃ + Y₂O₃ | [91] Synthesis of functionally graded (FG) α-β sialon by hot pressing process | Crack- and defect-free α/β sialon functionally graded materials (FGM) with outstanding joint interface have been fabricated | ↓ |
| Si₃N₄ + AlN + Y₂O₃ | [55] Temp. effect on the mechanism of α-sialon formation | The main factor that considerably affected the rate of α-sialon formation was the sintering temperature. Oxygen conc. and small variation in the composition of precursors did not affect the rate considerably | ↓ |
| β-Si₃N₄ + α-Si₃N₄ + SiC | [92] Effect of SiC on tribological performance of sialon ceramics | SiC did not affect at all the tribological response of the synthesized sialons | ↑ |
| Si + α-Si₃N₄ + Al + SiO₂ | [76] Pressure effect of N₂(g) on morphology and crystallinity of sialons | Single-phase, highly-crystalline and rod-like α-sialons have been successfully prepared | ↓ |
| Si + Si₃N₄ + AlN | [77] Effect of AlN addition on sialon synthesis | AlN has not improved Si₃N₄O phase formation and has encouraged single-phase sialon formation | ↓ |
| Si₃N₄ + Al₂O₃ + Y₂O₃ | [93] Investigation properties of the prepared β-sialon ceramics without and with sintering aid (1 wt. % Y₂O₃) | Single-phase composition of β-sialon without residual amorphous grain-boundary phase have been successfully prepared in absence of yttrium oxide; however, a small amount of glassy phase has been formed in presence of yttrium oxide sintering aid | ↓ |
| α-Si₃N₄ + Al₂O₃ + Fe₂Al | [94] Effect of addition of different raw materials on β-sialon formation and its intrinsic characteristics | Fe₂Al addition has improved mechanical properties of β-sialon composite and its formation too | ↓ |
| Si + α-Si₃N₄ + Al + Y₂O₃ + SiO₂ | [78] Effect of addition of NH₃/F additive and β-sialon diluent on the morphology and polymorphism of sialon products | Utilization of β-sialon as a diluent motivated β-sialon whiskers formation. Synthesis of β-phase was also favored with addition of high amounts of NH₃/F. Additive and diluent contents controlled to high phase polymorphism and microstructure of β-sialon whiskers | ↓ |
| α-Si₃N₄ + Al₂O₃ + AlN + Y₂O₃ | [56] Effect of atmosphere on β-sialon materials corrosion | In a gaseous atmosphere like Cl₂, CO₂, SO₂, H₂ or sulfur vapor, the liquid phase formation increases significantly and the corrosion resistance of β-sialon ceramics deteriorates considerably | ↓ |
| α-Si₃N₄ + α-Al₂O₃ + AlN + Y₂O₃ | [57] Sintering temperature effect on microstructure of β-sialons | At 1700°C, single-phase β-sialon has been obtained, whereas at 1725°C and 1750°C, traces of yttrium aluminum silicon oxide nitride material were noticed together with β-sialon | ↓ |
| α-Si₃N₄ + α-Al₂O₃ + Y₂O₃ | [58] Effect of Al₂O₃ addition on sintering behavior of sialons | Low density O -sialon ceramics have been successfully fabricated by altering α-Al₂O₃ amount at low sintering temperature. Single-phase composition of O -sialon was synthesized in the sample containing about ~10.42 wt.% α-Al₂O₃ | ↓ |
| α-Si₃N₄ + boron-rich slag + silica fume + bauxite chalmette + carbon black | [95] Effect of the gradual addition of α-Si₃N₄ on the α-sialon formation | α-Sialon content has increased with the gradual increase of α-Si₃N₄. Aspect ratio and amount of elongated α-sialon grains could be adjusted using variant amounts of α-Si₃N₄ | ↑ |
| Si₃N₄ + AlN + Y₂O₃ | [96] Effect of silicon nitride powders on the preparation of α-sialon ceramics | α-Sialon synthesis necessitates liquid phase, but is not highly affected by the amount and composition of this glassy phase. | ‡ |
| Si₃N₄ + SiO₂+ Al + AlN | [97] Effect of sample stoichiometry on the combustion characteristics of sialon | α + β-Sialon ceramics have been produced with elongated grains and high aspect ratio. Further, β-sialon content in the prepared (α + β)-ceramics has increased with the increase of β-Sialonamounts Increasing the solid load percentage was found to decrease porosity and change pore size and struct | ‡ |
| α-Si₃N₄ + Al₂O₃ + AlN | [98] Effect of suspension solid load on characteristics of the produced porous ceramics | Increasing the solid load percentage was found to decrease porosity and change pore size and structure result in improving the compression resistance | ‡ |
| Si₃N₄ + Al₂O₃ + AlN | [59] Effect of excess oxide and silicon oxide vapor on densification properties | Highly efficient β-sialon with superior strength were obtained by heating mixture of Si₃N₄ and SiO₂ under adequate SiO under pressure that basically prohibited thermal decomposition of the prepared sialons | ‡ |
| α-Si₃N₄ + CaCO₃ + Yb₂O₃ + Si + Al + AlN + SiO₂ + Fe₂O₃ + NH₃/F | [79] Effect of different starting stoichiometric compositions on the characteristics of produced sialons | Particle size and morphology of the synthesized Yb-doped α-sialon robustly affected by initial compositions. Fine or coarse rod-like sialon particles were synthesized with various metal to nitride ratios, and massive rod-like crystals were synthesized in presence of seed crystal | ‡ |
| Si₃N₄ + Al₂O₃ + Y₂O₃ + AlN | [99] Effect of sintering conditions on densification properties of sialon ceramics | Different types of sialon ceramics have been fabricated with relative densities of a direct relationship with the amount of liquid-phase formed during the sintering process | ‡ |

(Continued)
| Starting materials | Parameters studied | Important results | Synth. proc. |
|--------------------|--------------------|------------------|-------------|
| α-Si₃N₄ + Al₂O₃ + AlN | 100 | Sintering temperature effect on characteristics of synthesized sialons | High-density sialon ceramics have been synthesized without using any sintering aid. Strength was deteriorated at 1300°C and 1400°C, due to the subcritical crack growth that occurred due to grain-boundary sliding |  |
| α-Si₃N₄ + β-Si₃N₄ + Y₂O₃ + Si + Al + AlN + Si₃N₄ + NH₄F | 80 | Effect of initial stoichiometric compositions on grain size and morphology of sialons | Rod-like crystals of Y₃-O₃-sialons powders were fabricated using α-sialon seeds and NH₄F. Excess NH₄F has encouraged β-sialon formation at the expense of α-sialons | ‡ |
| β-Si₃N₄ + Al₂O₃ | 101 | High-energy milling effect on densification and phase evolution of sialon ceramics | Densification mechanism and phase transformation of high-energy milled powder was found to be mainly dependent on the solution-diffusion-reprecipitation from homogeneous glassy Al–Si–O–N phase formed on nano-β-Si₃N₄ grains | ‡ |
| α-Si₃N₄ + Al₂O₃ | 102 | Effect of initial composition (x) on polymorphism of Al₃Si₁₂₋ₓAlₓO₃N₁₆₋ₓ (M = 0.5Ca+0.5Mg) | α-sialon together with AlN-polytypoidal phase were formed when x ≥ 1.0, and AlN content was found to have a direct proportion to the x value | ‡ |
| α-Si₃N₄ + Al₂O₃ | 103 | Sintering temperature effect on sialon phase formation | Sintering temperature highly affected the phase composition of the synthesized sialon ceramics where multiple phase sialon composites along with yttrium aluminum garnet (YAG, Y₃Al₅O₁₂), corundum (α-Al₂O₃) and mullite have appeared at the different sintering temperatures | ‡ |
| α-Si₃N₄ + Si + Al + Al₂O₃ + Y₂O₃ + Yb₂O₃ | 81 | Reaction parameters effect on sialon microtube growth | Highly crystalline sialon microtubes have been synthesized at >1900°C with ~10°C s⁻¹ heating rate and 6 MPa N₂ pressure | ‡ |
| α-Si₃N₄ + Y₂O₃ + Si + Al + AlN + SiO₂ | 82 | Effect of Fe₂O₃ addition on the development of Y-doped-o-sialon whiskers | Fe₂O₃ addition has facilitated the development of Y-o-sialon whiskers and enhanced their aspect ratios and lengths | ‡ |
| α-Si₃N₄ + Al₂O₃ + Y₂O₃ + Sm₂O₃ + CaO | 105 | Sintering temperature and stress effect on the creep of sialon ceramics | α/β-Sialon composites with mullite as a secondary crystalline phase have been prepared. With elevating the sintering temperature, mullite phase content has increased at the expense of the intergranular glassy phase result in improving the creep resistance of the synthesized ceramics | ‡ |
| α-Si₃N₄ + Al₂O₃ + Y₂O₃ | 106 | Effect of phase composition and content of α-sialon on characteristics of sialon | The fracture toughness values have decreased with increasing α-sialon content, whereas the hardness values have showed a reverse effect | ‡ |
| α-Si₃N₄ + Al₂O₃ + CaO | 107 | Effect of hot press characteristics of prepared sialon | Highly dense Lu-o-sialon ceramics with an equiaxed texture and grain size of ~1 μm have been produced by hot pressing at 1950°C for 2 h in a N₂ atm. These ceramics have revealed outstanding mechanical properties and high optical transmission ~70% | ‡ |
| α-Si₃N₄ + Al₂O₃ + SiO₂ | 108 | Effect of hot press and particle size reduction on characteristics of sialon ceramics | Translucent Y-doped α-sialon ceramics have been prepared at 100–150°C lower temperature compared to the pressure-less sintered specimens; and the high fineness of the starting materials has significantly reduced the sintering temperature | ‡ |
| α-Si₃N₄ + Al₂O₃ + Y₂O₃ | 60 | Y₂O₃ addition effect on the properties of β-sialon ceramics | Single-phase β-sialon of a comparable grain size was synthesized with and without yttria addition | ‡ |
| Si₃N₄ fused alumina + Al₂O₃ + Al | 109 | Thermodynamics calculations have been done to interpret β-sialon formation during sintering | β-sialon was formed at 1300°C as a reinforcing phase in the Al-Si₃N₄-Al₂O₃ composite due to the high stability of Si₃AlON, compared to Al₂O₃ at 1300°C in an N₂ atm | ‡ |
| α-Si₃N₄ + (Al(O-i-Pr)₃) + Al₂O₃ | 110 | Effect of microstructure on strength and fracture toughness of β-Sialon | β-Sialon with elongated grain texture, high aspect ratio and a small amount of O-β-sialon phase has revealed low strength and fracture toughness characteristics | ‡ |
| α-Si₃N₄ + α-Al₂O₃ + Si + Al + CaO + Y₂O₃ + TiO₂ + Fe₂O₃ | 111 | Effect of sintering temperature, yttria, titania, and Fe₂O₃ additives as well as α-Si₃N₄ seeds on the preparation of Ca-o-Sialon | Ca-o-Sialon powders were prepared after 8–20 h at 1550°C and promoted by addition of Y₂O₃ and TiO₂ additives more than that of Fe₂O₃. Addition of α-Si₃N₄ seeds has also motivated the Ca-o-Sialon formation | ‡ |
| Si₃N₄ + Al₂O₃ + Y₂O₃ | 61 | Effect of starting materials on sintering and characteristics of sialon ceramics | Vickers hardness of the synthesized sialon ceramics increased with the amount of o-sialon phase; and sintering temperature of sialon ceramics fabricated from Si₃N₄-Al₂O₃ composite was lower than that of those made from separate nanocomposites | ‡ |
| α-Si₃N₄ + Al₂O₃ + Nd₂O₃ | 112 | Effect of hot pressing on characteristics of produced sialon ceramics | Two-step hot pressing process gave rise to highly dense Nd-o-sialon ceramics consisting of elongated grains with high aspect ratio embedded in finer equiaxed grain | ‡ |

(Continued)
Table 2. (Continued).

| Starting materials | Parameters studied | Important results | Synth. proc. |
|-------------------|--------------------|-------------------|-------------|
| \(\alpha\)-SiN\(_4\) + AlN + Al\(_2\)O\(_3\) + \(\gamma\)-Si\(_3\)N\(_4\) + \(\beta\)-Si\(_3\)N\(_4\) | Effect of alkaline earth or rare earth elements on microstructure of sialon ceramics | Excess of rare earth cations resulted in the formation of \(\alpha\)-sialon-rich materials with elongated particles and high toughness | ↑ |
| \(\alpha\)-SiN\(_4\) + AlN + Al\(_2\)O\(_3\) + \(\gamma\)-Si\(_3\)N\(_4\) + \(\beta\)-Si\(_3\)N\(_4\) | Hot-pressing effect on microstructure and mechanical characteristics of synthesized sialon ceramics | Highly dense, fine-grained single-phase composition of \(\gamma\)-sialon with enhanced mechanical properties and high transmittance has been successfully prepared by two-step hot pressing process | ↓ |
| \(\alpha\)-SiN\(_4\) + Y\(_2\)O\(_3\) + Si + Al + Si\(_2\)O\(_3\) | Sintering temperature, heating rate, and addition of seed crystals effect on characteristics of synthesized sialon ceramics | Highly dense \(\beta\)-\(\alpha\) -sialon ceramics reinforced with rod-like particles have been fabricated by SPS at low temperature (1600°C). Addition of seed crystals has facilitated phase transformation, boosted the grain growth and developed rod-like grains of the sintered samples | ↓ |
| \(\alpha\)-SiN\(_4\) + Si\(_2\)O\(_3\) + AlN + CaO | Effect of AlN precursor on development of Ca-\(\alpha\)-sialon phase | 50 nm AlN has led to formation of \(\beta\)-sialon phase for a starting composition that usually gives rise to \(\alpha\)-phase. Fracture toughness increased with decreasing the size of AlN powder from 1 μm to 50 nm | ↓ |
| \(\alpha\)-SiN\(_4\) + AlN + Al\(_2\)O\(_3\) + poly carboxylic ammonium salt | Effect of composition (2) on mechanical properties and microstructures of Si\(_6\)Al\(_2\)O\(_{17}\) sintered bodies | \(\beta\) -sialon ceramics (with \(z \geq 2\) in the range from 0.5 to 1) with 600 MPa flexural strength have been prepared, and fracture toughness had its maximum value (4.1 MPa m\(^{1/2}\)) at \(z = 2\) equals ~ 0.5. | ↓ |
| Si\(_2\)N\(_4\) + AlN + Al\(_2\)O\(_3\) | Phase structure effect on mechanical properties of synthesized sialon | Two-phase structure Al\(_2\)O\(_3\) -sialon ceramic composites have been successfully synthesized with enhanced fracture toughness where the two phases formed continuous networks and they were entangled and tightly bonded to each other | ↓ |
| Si\(_2\)N\(_4\) + AlN + Al\(_2\)O\(_3\) + Y\(_2\)O\(_3\) | \(\beta\)-Si\(_3\)N\(_4\) addition effect on toughness of prepared sialon | \(\beta\)-Si\(_3\)N\(_4\) whiskers were more effective compared to the in-situ grown \(\beta\)-Si\(_3\)N\(_4\) grains in strengthening \(\alpha\)-sialon | ↓ |
| \(\beta\)-Si\(_3\)N\(_4\) + Si + Al + Al\(_2\)O\(_3\) | Vapor-liquid-solid (V-L-S) mechanism effect on morphology of sialons | V-L-S mechanism is the leading technique for producing rod-like and whiskers \(\beta\)-sialon crystals | ↓ |
| \(\alpha\)-SiN\(_4\) + AlN + CaCO\(_3\) | Effect of sintering technique on microstructure of produced sialon ceramics | Fine-grained, bimodal microstructures Ca-\(\alpha\)-sialon has been fabricated via hot pressing process, whereas elongated grains with high aspect ratio have been prepared by pressureless sintering | ↓ |
| \(\alpha\)-SiN\(_4\) + Al\(_2\)O\(_3\) + AlN + Lu\(_2\)O\(_3\) | Excess Lu\(_2\)O\(_3\) effect on properties of Lu-\(\alpha\)-sialon ceramics | Elongated \(\alpha\)-sialon grains and their aspect ratio were found to increase with the increase of Lu\(_2\)O\(_3\) content; further increase of Lu\(_2\)O\(_3\) content above ~ 4 wt.% has led to reduction of the size of \(\alpha\)-sialon grains. Lu-\(\alpha\)-sialons containing extra Lu\(_2\)O\(_3\) demonstrated high hardness, toughness and flexural strength | ↓ |
| \(\alpha\)-SiN\(_4\) + AlN + MgO | Microstructure effect on the characteristics of Mg-\(\alpha\)-sialon ceramics | Densification, optical and mechanical characteristics of Mg-\(\alpha\)-sialon ceramics were influenced by \(\alpha\)-phase ratio and all these characteristics were adjusted by monitoring the amount of intergranular glassy phase and adjusting sintering parameters | ↓ |
| \(\alpha\)-SiN\(_4\) + AlN + \(\gamma\)-Y\(_2\)O\(_3\) + Nd\(_2\)O\(_3\) + \(\gamma\)-Y\(_2\)O\(_3\) | Effect of \(\alpha\)-sialon seed crystals on the texture of produced sialons | Single-phase composition of \(\alpha\)-sialon with elongated grains and greatly improved fracture toughness together with preserving high hardness has been prepared via seedding | ↑ |
| Si\(_2\)N\(_4\) + BaCO\(_3\) + AlN + Al\(_2\)O\(_3\) | Sintering temperature effect on properties of Ba-containing-sialons | Fully dense Ba-\(\alpha\)-sialon ceramics have been prepared via hot pressing at 1750°C for 2 h, whereas the best mechanical characteristics have been obtained at 1700°C | ↓ |
| \(\alpha\)-SiN\(_4\) + Al\(_2\)O\(_3\) + MgO + La\(_2\)O\(_3\) | La\(_2\)O\(_3\) addition effect on properties of produced sialons | Addition of La\(_2\)O\(_3\) has considerably improved densification properties of Mg-\(\beta\)-sialon ceramics | ↓ |
| \(\alpha\)-SiN\(_4\) + AlN + CaCO\(_3\) | Effect of Si\(_3\)N\(_4\) precursor powders on characteristics of synthesized sialon ceramics | Ca-\(\alpha\)-sialon morphology was not influenced considerably by the various kinds of Si\(_3\)N\(_4\) starting powders, whereas elongated grains were formed in all compacts regardless of the type of Si\(_3\)N\(_4\) starting powders | ↓ |
| Si\(_2\)N\(_4\) + AlN + CaO + CaCO\(_3\) | Effect of sintering temperature on sialon phase formation | Ca-\(\alpha\)-sialon started to form at 1300°C, and its content has increased with the sintering temperature until complete conversion at 1700°C. CaSiO\(_3\) has appeared between 1400°C and 1500°C and remained in the synthesized materials even at ~1700°C | ↑ |
| \(\alpha\)-SiN\(_4\) + \(\gamma\)-Y\(_2\)O\(_3\) + Yb\(_2\)O\(_3\) + Si + Al + AlN + Si\(_2\)O\(_3\) | Effect of quenching technique on microstructure evolution of \(\alpha\)-sialon ceramics | Rod-like Y-\(\beta\)-Yb-co-stabilized \(\alpha\)-sialon materials have been successfully prepared by quenching technique | ↓ |
| \(\alpha\)-SiN\(_4\) + Al\(_2\)O\(_3\) + AlN + \(\gamma\)-Y\(_2\)O\(_3\) | Effect of processing variables on the microstructural features and the mechanical properties of sialon | The maximum density was obtained for the 10% added elongated reinforcing agent | ↓ |
| Si\(_2\)N\(_4\) + AlN + Dy\(_2\)O\(_3\) | Effect of temperature on sialon phase content | Dy-doped-\(\alpha\)-sialon ceramics have been synthesized and stabilized over a large temperature interval | ↓ |
Table 2. (Continued).

| Starting materials | Parameters studied | Important results | Synth. proc. |
|--------------------|--------------------|-------------------|--------------|
| From Si₃N₄        |                    |                   |              |
| Si₃N₄ + mullite (sol-gel) + Al₂O₃ + SiO₂ | Effect of mixing conditions on X-sialon formation | Combination of ultrasonic and magnetic stirring were found to be the most suitable mixing process to get a single-phase X-sialon free of unreacted Si₃N₄ | ‡ |
| α-Si₃N₄ + CaCO₃ + MgCO₃ + SrCO₃ + Yb₂O₃ + Si + Al + SiO₂ | Effect of Ca incorporation on the phase composition and grain morphology of reaction products | Incorporation of Ca has encouraged the growth of rod-like α-sialon crystals in (Ca+Mg) and (Ca+Yb) systems | ‡ |
| α-Si₃N₄ + CaCO₃ or CaO + Si + Al + SiO₂ | Effect of growth mechanism on Ca α-sialon crystals | Rod-like Ca-α-sialon crystals have been synthesized; these rod-like crystals are attractive in fabricating toughened α-sialon ceramics than equiaxed ones | ‡ |
| Si₃N₄ + Activated carbon + fly ash | Effect of Si content, sintering temperature and N₂ pressure on sialon synthesis | The increase of all studied parameters (Si content in specimens, sintering temperature and N₂ pressure) were found to have a positive effect on the nitrification synthesis of sialon | ‡ |
| α-Si₃N₄ + Y₂O₃ + Si + Al + SiO₂ | Effect of starting composition on the phase assemblage of combustion products | The oxygen content during the reaction was found to have a considerable effect on polymorphism of the sialons, where the phase changed gradually from single-phase α-sialon to β-sialon with the rise of oxygen content | ‡ |
| α-Si₃N₄ + MgO + Al₂O₃ + Y₂O₃ + AlN + MgF₂ | Effect of sintering temperature, time and fluoride addition on characteristics of sintered sialons | Fluorine addition as an additive revealed a positive effect on mechanical and densification properties of produced sialons; F-doped sintered β-sialon composites demonstrated better density values and less apparent porosity at lower temperatures compared to the fluorine free specimens; fully dense F-doped-β-sialon compacts have been produced at 1700°C for 60 min | ‡ |
| Si₃N₄ + Al + AlN | Effect of Al content on mechanical characteristics of sialon ceramics | 10 vol.% Al gave rise to compacts with four times higher in strength than those being prepared without Al additives | ‡ |
| β-Si₃N₄ + Y₂O₃ and/or Re₂O₃ + Sm₂O₃ + CaCO₃ | Effect of powder processing conditions on characteristics of produced sialon parts | Sialons ceramics fabricated from commercial Si₃N₄ powders have showed comparable wear resistance values and better durability than commercial alumina-based ceramics; silica amount on Si₃N₄ powder has controlled the phase assemblage; particle size of starting powders has had vital effect on microstructure evolution | ‡ |
| β-Si₃N₄ + Al₂O₃ + AlN + Y₂O₃ + BaCO₃ + SiO₂ | Effect of sintering temperature on grain growth and phase transformation of produced sialon ceramics | SPS at 1800°C for 5 min is totally enough for complete formation of highly dense, elongated grained Y-α-sialon ceramics | ‡ |
| Si₃N₄ + AlN + Al₂O₃ + SiO₂ + Li₂CO₃ | Effect of SiO₂ and Al₂O₃ additions, holding time and packing powders on the properties of Li-α-sialon products | Single-phase composition of Li-α-sialon has been successfully produced at 1700°C for 1 h and at 1050°C for 1 h in BN-Li─Si-Al─O–N packing powder, together with SiO₂ and Al₂O₃ additives where the latter conditions have retarded Li vaporization and accelerated Li-α-sialon formation | ‡ |
| From Minerals |                   |                   |              |
| Natural pyrophyllite + liquid resin | Mechanism of β-sialon growth | β-Sialon growth has followed vapor-liquid-solid (V-L-S) mechanism and presence of Fe₂O₃ has significantly affected on the growth mechanism | ‡ |
| Kaolinite (BEL, India) + carbon black | The suitability of using microwave irradiation in sialon fabrication | β-Sialon has been successfully produced from kaolinite under microwave irradiation, and produced sialons have possessed comparable mechanical properties to the conventionally sintered sialon ceramics | ‡ |
| Kaoiln (Russian deposit) + colloidal graphite | Carbon content and heating regime effect on β-sialon formation | Highly porous β-sialon have been successfully prepared in this work; these sialons could be used as membrane materials | ‡ |
| Andalusite + Si + Al sources without/with TiO₂ or Y₂O₃ | Effect of various synthesis parameters and starting precursors on the properties of synthesized sialons | Highly crystalline X-sialon ceramics with minor amounts of other phases have been synthesized via controlling synthesis parameters and starting materials | ‡ |
| Iranian kaolinite + polycrylamid | Firing temperature, holding time and N₂ gas flow rate effect on nano-powder β-sialon formation | Nano-crystalline β-sialon powder has been produced starting from kaolinite and polyacrylamide as a reducing agent at 1500°C for 3 h under N₂ atm (3 L/min); the yield was about ~85 wt.%, together with SiC and Si₃N₄ impurities | ‡ |
| (kaolin or SiO₂/Al₂O₃) + Carbon | Effect of N₂ (pressure & flow rate) and reaction (time & temperature) on sialon formation | Single-phase β-sialon powder has been synthesized starting from kaolin or Al₂O₃/SiO₂ mixtures at ~1600°C for 2 h, under 30 bar and ≥21 L/min N₂; lowering N₂ pressure did not produce single-phase β-sialon; and elevated N₂ pressure diminished evaporative losses of SiO₂ | ‡ |
| Kaolins ((LO)T3 Ward Rd, East Rockingham, WA) + Si + Al | Effect of firing temperature on microstructure evolution of the produced sialons | Monophasic, submicron-sized β-sialon powders have been fabricated from kaolin at low firing temperature decreasing particle agglomeration and synthesis cost | ‡ |

(Continued)
| Starting materials | Parameters studied | Important results | Synth. proc. |
|-------------------|--------------------|------------------|-------------|
| Halloysite (NZ) + China Clays + carbon | [140] Effect of grinding and heating on carbothermal sialon precursors | Grinding of precursors for 12 h satisfactorily enhances the desired sialon formation on subsequent heating under nitrogen. |  |
| Clay + Si + Al₂O₃ | [141] MgO, Y₂O₃ and Fe₂O₃ additives effect on sintering behavior of sialon ceramics | X-sialon formation has been motivated by MgO addition; sintering behavior was totally independent on additive concentration |  |
| Kaolin + carbon + silicon carbide | [142] Effect of Si-bearing materials on sialon characteristics | β-Sialon was possibly synthesized from raw kaolin with high SiO₂ content of up to 44 wt. % |  |
| Kaoalinite + carbon black | [143] Effect of firing temperature and N₂ flow rate on sialon powder formation | β-Sialon was produced as a major phase, together with minor amounts of Al₂O₃ and mullite; firing temperature and N₂ flow rate affected considerably on reaction rate phases formed |  |
| Kaolin + carbon black | [144] Firing temperature, holding time, N₂ flow rate and carbon black content effect on β-sialon powder formation | Monophasic β-sialon powder was successfully synthesized at ~1450 °C for 6 h, under N₂ flow at a rate of 2.5 L/min; excess 5 wt.% carbon has favored carbothermal reduction of kaolin; excessively high firing temperatures and carbon amount have led to SiC formation; keeping N₂ flow rate at a high level was an advantage for synthesis of β-sialon and prevention SiC formation |  |
| Kaolin + carbon + silicon carbide + iron | [145] Effect of firing temperature and iron content on β-sialon formation | Monophasic β-sialon was synthesized starting with no more than 1 wt. % iron additives where high iron content was found to encourage iron silicide formation |  |
| Si + Halloysite clay + Al₂O₃ + AlN + SiO₂ | [146] Effect of firing temperature, N₂ pressure and additive type on the characteristics of sialons | O and β-sialons have been prepared by silico thermal and reaction bonding processes; sintering aids affected considerably on sialon densification and firing temperature affected significantly on sialon decomposition |  |
| (Clay-carbon-Nitrogen Montmorillonite), (Boehmite-silica-SiC-carbon Nitrogen) and (Si₃N₄ + Al₂O₃) | [68] Effect of firing temperature and time on β-sialon formation | β-Sialon has been microwave synthesized at 1500 °C after 15 min; Conventionally synthesized β-sialon has been obtained at higher temperature and longer time; β-sialon was difficult to be prepared from (clay-carbon) or (Boehmite-silica-SiC-carbon) system |  |
| Halloysite clay + talc + Carbon Black | [147] Carbon content, firing temperature and time effect on sialon synthesis | Mg₀-β-sialon has been prepared with a yield of 90 wt.% at 1480 °C for 4 h using talc to halloysite ratio of 1.5 and 2.0 |  |
| Kaolin (Ksythmy deposit) + carbon | [148] Effect of calcination temperature of kaolin on properties of prepared sialon ceramics | X-β β-sialon ceramics have been successfully prepared using various calcined kaolin products synthesized at different calcination conditions |  |
| Zeolite + carbon black | [149] Effect of mixing conditions on carbothermal reduction nitridation of aluminosilicates | β-Sialon and α-Si₃N₄ have been detected as the basic crystalline phases from zeolite-carbon mixtures |  |
| Kaolin + SiC + Al + Si + perlite | [150] Effect of sintering temperature on sialon formation | β-Sialon has been formed starting from SiC-Al and Si powders at 1450 °C and from Si₃N₄, Si and AlN at 1250°C – 1300°C |  |
| Clay (from Shan-dong Province of China) + carbon | [151] Sintering temperature, holding time, N₂ flow and carbon content effect on sialon synthesis | The highest β-sialon phase percentage has been obtained at 1450°C for 6 h with 20 wt. % carbon additive and 1.5 L/min N₂ flow |  |
| Natural montmorillonite + Al₂O₃ | [152] Effect of pillaring clay with Al₂O₃ on β-sialon synthesis | β-Sialon has been synthesized from clay pillared with Al₂O₃ at a considerably lower temperature than from unpillared mixture; pillared samples gave rise to higher β-sialon yield at faster reaction rate |  |
| Coal gangue + activated C | [153] Si and carbon additives effect on O-sialon formation | O-sialon was prepared more efficiently using Si additive than activated carbon |  |
| Geopolymers + Al powder + Si + SiC + Al₂O₃ | [154] Effect of nitro aluminothermic processes on phases formation | Sialon composite composed of β-sialon, SiC and corundum has been successfully prepared by the nitro aluminothermic process |  |
| Clay + C + Al₂O₃ + fly ash | [155] Effect of dispersants and reaction (temperature and time) on amount and type of sialon phases | The best processing parameters of slip casting that gave rise to highly toughened sialon ceramics are 1.5 wt.% polyelectrolyte and ball-milling for 12 hours; the best sintering parameters are 1500 °C for 4 hours |  |
| Coal gasification slag from Texaco coal gasifier | [156] Effect of nitridation temperature on sialon phases formation | β-Sialon along with mullite and Ca-o-Sialon as minor phases were appeared at 1350 °C; Sialon powder with Ca-o-Sialon as main crystalline phase was prepared at 1500 °C |  |
| Kyanite tailings from Gansu Province, China + Carbon coke + Si₃N₄+SiC + SiC composite | [157] Effect of sialon-SiC substituent amount on mechanical properties of sialon/Si₃N₄-SiC composite | Sialon/Si₃N₄-SiC composite with volume density of ~2.03 g/cm³, bending strength of ~41.8 MPa and compression strength of 61.6 MPa has been obtained by addition of 25 wt. % sialon-SiC |  |
| A red schist from the coal mine in Decazeville (Massif Central, France) | [158] Effect of carbon content, reaction (time and temperature) on formation of sialon phases | Low carbon percentage (10 wt. %) has led to mullite formation even at 1500°C; for 20 wt. % carbon, a mixture of sialons (X, Ø, O) has been obtained at 1500°C, pure phase of β-sialon has appeared at 30 wt. % of carbon and 1400 °C for 2 hours |  |

(Continued)
Table 2. (Continued)

| Starting materials | Parameters studied | Important results | Synth. proc. |
|--------------------|--------------------|-------------------|-------------|
| Kaolin (from the Proksanovskoe deposit) + caron | [159] Effect of temperature on phases formation | β-Sialon powder was prepared at high temp. (1700–1800°C). At temperatures below 1500°C, silicon carbide and aluminum oxide are formed; at higher temperatures, silicon carbide and aluminum carbide are formed. | † ††† |
| Halloysite clay + alumina + elemental silicon | [160] Effect of inorganic oxide additives on formation and densification of X-sialon | Densification of produced X-sialon has improved by the additives following the order: Y2O3, CaO and CeO2 followed by MgO; melture conversion to X-sialon at high temperature happened in presence of Y2O3, CaO and MgO, but was suppressed by Fe3O4. | †††† |
| Zeolite | [161] Effect of concentration and injection timing of C3H8 on the phase compositions of the products | O- and X-sialon phases have appeared at lower C3H8 concentrations; O-sialon has increased and X-sialon has decreased with the increase of C3H8conc. O-sialon and X-sialon has been formed by introduction of C3H8 at 1300 and 1400°C, pure β-sialon has been successfully obtained when C3H8 was introduced at 1200°C | †††† |

**From industrial wastes**

| From industrial wastes | Parameters studied | Important results | Synth. proc. |
|-----------------------|--------------------|-------------------|-------------|
| Chinese coal gangue + Si and Al powders | [162] Different atm. effect on sialon phases | Different types of sialon such as β-sialon and O-sialon with different contents were prepared depending on the synthesis atm. | † |
| Fly ash + lignite chars or/and graphite | [163] Effect of C content, reaction (temp.& time) and reductant type on the composition of synthesized sialon | β-Sialon in a rod like whiskers with small amount of β-sialon in beads like structure have been successfully prepared via controlling the studied parameters | †† |
| Fly ash + Carbon | [164] Effect of C content, temp. regime and N2 flow rate on the β-sialon synthesis | With controlling operating parameters, a highly pure β-sialon with higher nitrogen contents has been successfully synthesized | †† |
| Al dross (Toyo Aluminum Co. ltd., Hino, Japan) + AlN+ Al + Al2O3 | [86] Effect of changing the reclaimed Si powder and N2 pressure of reactant on nitridation reaction | Al dross was successfully converted into β-sialon based ceramics where reaction could be sustained at 0.6 MPa N2 pressure and 40 wt.% of reclaimed Si; however, reducing the amount of reclaimed Si to 5 wt.% has stopped the reaction | †† |
| Fly ash + carbon black | [165] Effects of heating temperature and raw material compositions on sialon synthesis | β-Sialon-based composites were synthesized at 1723 K for 6 h using C black to fly ash mass ratio of 0.56; increasing heating temp. or mass ratio of carbon black to fly ash was found to promote β-sialon formation | †† |
| Aluminum dross + Si + SiO2 + Al | [166] Effects of temperature on the sialon composite synthesis | Monophasic β-sialon has been successfully produced by firing at 1000°C for 1 h | ††† |
| Fly ash + zircon + active carbon | [167] Effect of raw materials and holding time on the phase composition and microstructure of sialon products | Formation of β-sialon, 2ZnH and ZrON was promoted by increasing the carbon content and holding time; micron-sized (1–2 μm) β-sialon/2ZnH/ZrON composites have been successfully fabricated at 1550°C for 15 h | †† |
| Fly ash from Lagisza power plant (Poland) + carbon | [168] Effect of C content on phase composition of the carbothermal reduction product | Fly ash with high calica content has been converted into β-sialon or Ca-α/β-sialon based on carbon content applied | † |
| Waste-Si-sludge + Y2O3 + Al2O3 | [169] Effect of oxygen content on nitridation of waste Si compacts | Si3N4/O-sialon composites have been fabricated using Waste-Si Sludge by gas-pressure-sintering at 1950°C for 3.5 h; nitridation reaction of waste Si was quicker than that of commercial Si powders | †† |
| High aluminum fly ash + carbon black | [170] Effect of sintering temperature on β-sialon content | The highest yield of β-sialon was produced at 1400°C; β-sialon yield decreased with the temp. increase from 1400°C to 1500°C above 1500°C, β-sialon decomposed and the new phases of SiC and AlN have appeared formed | †† |
| Boron-rich slag + silica fume + bauxite chalmette + carbon black | [171] Effect of the starting material composition on the mechanical properties of Ca-α-sialon ceramics | Slag contained many impurities, which resulted in reduction of the mechanical properties of produced o-sialon; however, low cost and availability of slag made it more competitive compared to pure chemicals for α-sialon synthesis | †† |
| Gasification slag from texaco gasifier + carbon black | [172] Effect of nitridation temperature on the phase composition and morphology of sialon synthesis | The volume density, hardness and fracture toughness of synthesized Ca-o-sialon/SiC ceramic composite was improved by increasing the hot-pressing temperature | †† |
| Fly ash (from Shi Jing Shan electric power plant in Beijing) + carbon black | [173] Effect of temperature and C content on β-sialon synthesis | Monophasic β-sialon has been obtained at stoichiometric C content; SiC and SiAl2O3N3 appeared when excessive carbon was added; β-sialon content has increased with the increase of synthesis temperature | †† |
| Fly ash from the Reftinskaya thermal plant | [174] Effect of reaction (time and temperature) on phase compositions | β-Sialon has been appeared at 1450°C only after 3 h firing in N2 at reaction times longer than 240 min, Si-rich sialons decomposed partially and other compounds were formed | (Continued) |
| Starting materials | Parameters studied | Important results | Synth. proc. |
|-------------------|-------------------|------------------|-------------|
| Boron-rich blast furnace slag + silica fume + bauxite chamotte | [175] Effect of synthesis (temperature and holding time) on phase composition and microstructure of reaction products | α-Sialon synthesis has increased with the increase of the synthesis temperature or holding time; large number of elongated α-sialon grains has grown at higher temperature | † |
| Al recycling company shanghai Sigma metals inc. | [176] Effect of high temperature on characteristics of produced sialon ceramics | All the samples fabricated from 1450 to 1650°C consisted of β-sialon and Mg-AlN-poly-typoid; amount of β-sialon has increased whereas Mg-AlN-poly-typoid amount has decreased with the sintering temp. | † ‡ |
| From metals | | | |
| Al + Si + Al₂O₃ | [177] Effect of various Si metal sources on β-sialon compositions | β-Sialons of different compositions have been successfully prepared using different silicon sources | ‡ |
| Amorphous fumed silica, alumina and carbon | [7] Effect of time, temperature and microstructure on the reaction product | β-Sialon powder have been prepared and O'-phase formed at 1450°C as an intermediate; the surface area and porosity decreased as temperature increased; Carbon content decreased as time increased | ‡ |
| Si + Al + SiO₂ | [178] Effect of β-sialon diluents on the combustion temperature of the reaction | β-Sialon powder has been prepared at about ~2000°C, together with residual metal Si; both reaction temperature and amount of residual Si decreased gradually with the increase of diluent content up to 50 wt. %. At 50 wt. % dilution, the combustion temperature was 1859°C and complete conversion to pure β-sialon occurred | ‡ |
| BN + TiN + TiB₂ + SiC + ZrO₂ | [179] Effect of BN addition on friction and wear behavior on synthesized composites | The presence of BN in the sialon composite ceramics decreased the friction coefficient of the materials but also to negatively affect their wear resistance when the amount of BN exceeded 15 wt. % | ‡ |
| Si + Al + SiO₂ + B + BN+ SiC+ TiB₂ | [180] Effect of SiC, TiB₂ and BN on the properties of sialon composites | SiC and TiB₂ has improved strength and electrical conductivity characteristics of synthesized β-sialons, respectively | ‡ |
| Si + Al + SiO₂ + β-sialon powders (as a diluents) | [181] Effect of starting composition (z) on properties of β-Si₃.2Al₂O₃N₀.₈ | Pure β-sialon powders with the controlled z values (z = 2–4) have been prepared | ‡ |
| Si + Al + SiO₂ | [182] Effect of corrosion on the prepared β-sialons | β-Sialon powder prepared by combustion synthesis followed by spark plasma sintering could be severely corroded in supercritical water than in air and steam atmosphere | ‡ |
| Silica–alumina (Al-SBA-15) + poly 4-vinylpyridine (P4VP) | [183] Effect of carbon present and the surface area of the precursor on formation of nitride phase | β-Sialon phases have formed at 1450°C for 6 h via CRN method using approximately twice the stoichiometric amount of carbon | ‡ |
| Si + Al + SiO₂ | [184] Effect of diluents (β-sialon) on particle size and purity of synthesized powders | Particle size of produced β-sialons have significantly reduced in presence of the diluents | ‡ |
| Si + Al + SiO₂ + Al₂O₃ | [185] Effect of mechanically activated raw materials on β-sialon content | β-Sialon powders synthesized from mechanically activated reactants with low aluminum content demonstrated higher sialon content (88 wt. %) compared to inactivated reactants that had about ~67 wt. % β-sialons | ‡ |
| Si + Al + SiO₂ | [186] Effect of combustion synthesis (CS) and spark plasma sintering (SPS) on β-sialon synthesis | Combustion-synthesized β-sialon demonstrated more than 86% purity, whereas SPSed powders attained more than 99% of the theoretical density and higher purity | ‡ & |
| Si + Al + CaCO₃ + Y₂O₃+ NaCl + MgCl₂ | [187] Effect of metal chlorides on the α/β ratio and morphology of sialon products | NaCl additive gave rise to high α/β ratios and equiaxed grains, whereas MgCl₂ resulted in low α/β ratios and elongated structure | ‡ |
| Si + AlN + Al₂O₃ + ZrO₂ | [188] Effect of ZrO₂ addition on produced sialons | Highly-dense β-sialon ceramics have been produced with addition of ZrO₂ that promoted nitridation effect and acted as sintering aid for encouraging densification of β-sialon composites | ‡ |
| Al + Si + SiO₂ | [189] Effect of Si powder on sialon crystal shape | Single crystalline and granular conglomerates β-sialon nanowires have been obtained with and without addition of Si | † |
| Si + Al + Al₂O₃ + β-sialon + β-Si₃N₄ + SrCO₃ + NH₄F | [190] Effect of SiCO₂and NH₄F on β-sialon crystals synthesis | Novel β-sialon micro palings consisting of nanorods have been prepared with 2.0 wt.% SrCO₃ and 5.0 wt. % NH₄F | ‡ |
| SiO₂ + C + Al₂O₃ + CaSiO₃ | [191] Effect of temperature on Ca-a-sialon content | Single phase Ca-a-sialon was prepared and its content increased with increasing the firing temperature with highest content (>95 wt %) at 1700°C | ‡ |
| SiO₂ + Al₂O₃ + CaCO₃ + carbon | [231] Effect of the starting materials on the appearance of crystal phases in Ca₅Si₃Al₂₋ₓNₓO₁₀₋ₓ | Nano-hollow beads of Ca-a-sialon powders have been successfully prepared in this work; and multi-phases (o-sialon, β-sialon, and AlN) have formed by changing the starting composition (x) from 0.3 to 1.4 | ‡ |
| SiO₂ + Al₂O₃ + AlN + CaF₂ + carbon black | [232] Effect of o-Sialon seeding content on the properties of Ca-a-Sialon synthesized | o-Sialon seeding has motivated the formation of Ca-a-Sialon from short prismatic crystals to elongated structure | ‡ |
| Nano-alumina + silica sol gel | [233] Effect of sintering temperature and time on the properties of prepared sialon | Well-crystalline β-sialon powder with nanosized particle was obtained at 1300°C for 2–3 h | ‡ |
| ZrSiO₄ + γ-Al₂O₃ | [234] Effect of temperature on characteristics of sialon products | Long- and short-column-like ZrN-β-sialon composites have developed 1550°C and 1500°C, respectively | ‡ (Continued)
Table 2. (Continued).

| Starting materials | Parameters studied | Important results | Synth. proc. |
|--------------------|--------------------|-------------------|-------------|
| Si + Al + Al₂O₃ | [235] Effect of the catalyst type and amount on the weight gain of sialons | Addition of transition metals catalysts has led to increasing the weight gain rate of the samples 2–4 times, enhancing the nitridation of silicon and simplifying the development of β-sialon nanofibers | † |
| Si + Al + SiO₂ | [236] Effect of milling time on the reaction rate of CSed sialons | With the increase of ball milling time, conversion rate of β-sialon has increased | ‡ |
| Si + Al + Y₂O₃ + SiO₂ | [237] Effect of mechanical activation on the reaction activity of raw materials | Yttrium-stabilized α-sialon has been prepared where the reaction activity of metallic particles has elevated after being mechanically activated | ‡ |
| Si + Al + SiO₂ | [238] Effect of mechanical activation using ball mill on β-sialon synthesis | Fine-grained β-sialon was combustion synthesized at mild conditions using SiC content | ‡ |
| Si + Al + Al₂O₃ | [239] Effect of temperature on oxidation of elongated β-sialon material | Elongated β-sialon materials have displayed outstanding resistance to oxidation and the crystal shape was well retained up to 1373 K. | † |
| Si + Al + SiO₂ + KCl + MgCl₂ + CaCl₂ | [240] Effect of metal chlorides (KCl, MgCl₂, and CaCl₂) on β-sialon synthesis | Single-phase composition of β-sialon has been obtained with different morphologies using different chlorides; in addition, the size of β-sialon rod-like crystals became smaller with addition of KCl and they became coarser in presence of MgCl₂ or CaCl₂ | ‡ |
| SiO₂ + AlN | [241] Effect of milling time on the formation of β-sialon | Nanocrystalline β-sialon was prepared with high-energy ball milling after sintering at 1450 °C while and milled-powders for a short time required much higher sintering temperature | † |
| Si + Al + SiO₂ | [242] Effect of starting composition on the oxidation kinetics of β-Sialons Al₂O₃Nₓ, x ≈ ( z = 1, 2, and 3) materials | Oxidation kinetics have followed a parabolic behavior, and the variation from that rate was found to increase with the decrease of the z-value. The oxide products formed on β-sialon contained silica and Mullite. | ‡ & |
| Si(OH)₂ + Al(NO₃)₃ + H₂O + Fe(NO₃)₃ | [243] Effect of precursor compositions and sintering conditions on synthesized sialon | B-sialon content was enhanced with the increase of the sintering temperature and Si/C ratio | † |
| Si + Al + Al₂O₃ + α-SiC | [244] Effect of SiC addition on density, porosity and erosion of the prepared sialon | Density of sialon ceramics decreased with the increase of SiC level; unlike porosity and erosion resistance increased with elevated SiC | † |
| CaO + Al₂O₃ + SiO₂ | [245] Effect of the starting compositions (CaₓSi₁₋ₓAlₓO₃Nₓ) on the content of Ca-Sialon | Ca-a sialon and AlN increased and that of β-sialon decreased with increasing starting compositions value (x), except for the composition of x = 0.3, which had a relatively high α-sialon content | † |
| White silica-gel powder + aluminum powder + cobalt powder | [246] Effect of temperature on formation of sialon phases | β-Sialon along with other phases have been formed at 1400 and 1600°C with higher percentage of β-sialon at 1600°C; and other phases appeared at 1800°C as Al₂O₃-AlN and AlN with complete absence of β-sialon | † & ‡ |
| Water soluble alumina sol + silica sol | [247] Effect of temperature on formation of sialon phases | β-Sialon began to crystallize at 1300°C with Mullite, O-sialon and γ-sialon as intermediate phases. Nano-sized single phase β-sialon was obtained after heating at 1350 °C for 3 h | † |
| Tetraethyl silicate + Al(NO₃)₃ + H₂O + sucrose + citric acid | [248] Effect of β-sialon addition as crystal seed on the formation of sialon powder | Ultrafine β-sialon powder was formed and enhanced by adding small amounts of β-sialon as crystal seed, which had accelerated the formation of final β-sialon product and lower its formation temperature | † |
| Si + Al + SiO₂ | [249] Effect of starting composition on combustion-synthesized sialon powders | β-Sialon has been prepared via combustion synthesis under a low N₂ pressure | † |
| FeSiₓ alloy + α-Al₂O₃ | [250] Effect of alumina addition on physicomechanical properties of Fe-sialon ceramics | Fe-sialon ceramic matrix composite has been developed with better resistance to erosion wear compared to Al₂O₃ ceramic | † |
| Si + Al + SiO₂ + NaCl | [251] Effect of the amount of NaCl on sialon synthesis | NaCl diluent acted as a diffusion barrier and prevented grain growth of β-sialon particles, resulting in formation of submicron-sized β-sialon crystals | † |

†: Gas pressure sintering; ††: Pressure-less sintering; †‡: Combustion synthesis method; †*: Self-propagation high temperature; microwave sintering method; ††*: Carbothermal-reduction–nitridation; Spark plasma sintering; †**: Hot-pressing sintering; ††**: Gas-reduction nitridation; †††**: Aluminothermic nitridation method; ††††**: Silicothermic nitridation method; †‡‡: Slip casting. Reaction sintering; †‡‡*: Freeze casting; ††††**: Mechanical milling; †‡‡‡**: Ammonolysis.
3.1.4. Recent trends and future prospect in sialon usage for structural applications

Duplex α + β sialons-derived ceramics have achieved the utmost collection of mechanical properties, in between those of α- and β-monolithic sialons [29], where hardness and thermal shock resistance escalate and toughness as well as thermal conductivity diminish with the increase of α-phase percentage in the final sialon composite [1]. Also, fully crystalline ceramic or glass ceramic can be formed through crystallization of the oxynitride grain boundary glass achieved by post-annealing of sialon ceramics, which in turn improve elevated temperature properties. Complete devitrification of oxynitride grain boundary glass have raised the maximum operating temperature of β-sialon from ~1000 °C to 1400 °C [27]. Moreover, N content enhancing in the oxynitride glass increases its viscosity, glass transition temperature, elastic moduli, and hardness via increasing the crosslinking in this glass, leading to service temperature improvement [27]. Further, fabrication of graded sialon ceramics enriched at their surfaces by α-sialon would, respectively, take the advantage of high hardness of α-sialon and outstanding toughness of β-sialon at the surface and in the core of the fabricated ceramics (See Figure 6). This graded sialon ceramics will open the door wide for their utilization in the harsh-environment applications that require superior hardness and toughness such as automotive engines, high-performance bearings, wear components, cutting tools, gas turbine blades, and glow plugs. Physical lamination approach was found to be the best way to manage the thickness of α-sialon layer at the surface of the graded sialon ceramics depending on the targeted application [4, 202]. Accordingly, sialon-based ceramics have recently attracted an increasing attention as low-cost and outstanding alternatives to the currently used silicon nitride ceramics and metal alloys for the harsh-environment applications owing to their fast-growing commercial and technological significance.

3.2. Phosphor converted white LEDs

The major interest of ecofriendly products has increased utilization of light emitting diodes (LEDs) as light sources in communications, medical services, display backlighting, signage, and general lighting. Regarding general lighting, phosphor converted white LEDs (pc-WLEDs)
3.2.1. Phosphors

Phosphors are materials that emit light as a result of absorbing energy. They are composed of the host lattice such as CaWO4, YTaO4, Y2O3, and Y3Al5O12 and the activator such as Eu3+, Tb3+, Ce3+, or others. The activator is a dopant that makes substitutional defects in the host structure. They are commonly transition metals, main group metals, which are actually rare earth (RE) ions from lanthanides or a collection of alkaline earth metals, alkali metals, and otherwise unclassified metals. Ions activator with f-d or d-d electron configurations are the best choices for phosphors as they have the ability to emit a broad band and visible light under the effect of crystal field and nephelauxetic effect, which is a phenomenon that occurs when a decrease of the electronic transition energy meets an increase of the covalency [55, 56]. Classification of phosphors can be according to either their emission colors (i.e. red-, blue-, and green-emitting phosphors) or according to their chemical components [55]. In addition, some of phosphors are based on borates, nitrides, silicates, and phosphates.

3.2.2. Nitride phosphors

Among various types of phosphors, nitride compounds are characterized with their great diversity of crystal structures and variation of local structures that surrounding the activator ions, which can change the centroid shift and the splitting of crystal field of 5d energy levels of rare earth ions and lead to numerous releases of colors from nitride phosphors. Nitride phosphors can withstand against chemical or thermal attacks due to the structure stability of nitride host lattices against these conditions, which results in small degradation or thermal quenching of nitride phosphors. Nitride phosphors with their promising photoluminescent properties can be used in white LEDs as down conversion luminescent materials and form a new and important family of phosphor materials for lighting [57]. Among various kinds of nitrides, rare-earth (RE) doped-sialon materials have attracted significant attention as good phosphors for wLEDs due to the presence of two interstitial crystallographic sites in the crystal structure of sialons that could accommodate the rare earth activators such as Eu2+, Yb2+, Ce3+ and Pr3+. In the meanwhile, sialon host materials provide two extra merits over the conventional oxide-based host materials: (1) low excitation energy of the 5d electrons of activators due to the strong nephelauxetic effect (i.e. electron cloud expansion) originated from the covalent bonding nature between the activators and the ligands in sialon host; (2) low thermal quenching probability due to the rigid structure of sialon hosts with high Debye temperature, where the formal charge of N (−3) is higher than that of O (−2) and the covalent bond of Re-N is more stiff than the of Re-O. Furthermore, the high chemical and thermal stabilities of sialon phosphors is owing to their host lattice, which built on stiff frameworks consisting of Si-N or Al-O tetrahedra. In addition, a small thermal quenching and high conversion efficiency of

![Figure 6. Schematic of the sialon-graded ceramics.](image)

![Figure 7. (a) Di-chromatic pc-wLEDs; (b) Tri-chromatic pc-wLEDs; (c) Tetra-chromatic pc-wLEDs.](image)
phosphors occurs as the Stokes shift in a strong lattice becomes smaller [2]. Therefore, many nitride phosphors have been commercialized such as Eu$^{2+}$-activated β-sialon, α-sialon, and CaAlSiN$_3$ and played an important role in the production of reliable and highly efficient white LED product.

### 3.2.3. Sialon-based Yellow Phosphors

Ce$^{3+}$ or Eu$^{2+}$-activator ions with α-sialon host lattice primarily generate yellow radiations. The luminescence of Ce$^{3+}$ and Eu$^{2+}$ derives from 5d–4f transitions and is red-shifted from the blue/green to the yellow region due to the shift of 5d states to lower energy levels because of the stronger interactions between host materials and activator ions. In addition, electric dipole transitions are allowed by 5d-4f transitions, and hence, the emission from Eu$^{2+}$ and Ce$^{3+}$ is relatively bright, and these strong transitions are suitable for pc-WLED applications [5]. The large ionic radius of europium eliminated the formation of pure europium α-sialon, but the co-doping of yttrium or calcium allows the incorporation of europium into the α-sialon structure. Ca-Eu-sialon phosphor chromaticity can be managed by altering the composition. Combining blue LED chip with various Ca-Eu-sialon phosphors can produce white LEDs of color temperatures ranging from 1900 to 1300 K [59]. Fine yellow α-sialon: Eu$^{2+}$ phosphors have been prepared by Li et al. [203] using gas-reduction–nitridation method. The mentioned study has involved CH$_4$-NH$_3$ mixture gas as a reduction–nitridation agent and homogeneous mixture of the Ca–Eu–Al–Si–O system to obtain Eu$^{2+}$-doped Ca-α-sialon phosphors with a target composition of Ca$_{0.925}$Eu$_{0.075}$Si$_{0.9}$Al$_{1.2}$ON$_{13}$ prepared by a sol–gel process. According to Sakuma et al. [204], a yellowish orange high-efficiency Ca-Eu-sialon ceramic phosphor has been developed with composition of Ca$_{0.875}$Si$_{1.06}$Al$_{1.04}$O$_{1.98}$N$_{1.02}$Eu$^{2+}$0.07, where powders of Si$_3$N$_4$, Eu$_2$O$_3$, CaCO$_3$ and AlN were used as starting materials, well mixed by a planetary ball mill, and the synthesis process was applied by gas pressure sintering at 1700 °C for 50 h in a 0.5 MPa N$_2$ atmosphere. Xu et al. [205] have applied a novel mecanochemical activation to obtain fine Eu$^{2+}$-doped Ca-α-sialon phosphors, where the starting mixture with a nominal composition of Eu$_{0.75}$Ca$_{0.25}$Si$_{0.75}$Al$_{1.27}$O$_{1.12}$N$_{1.48}$ (x varied from 0.05 to 0.30) was mixed in ethanol and milled with planetary ball mill. Firing of the milled powders was done in BN crucibles under 0.5 MPa N$_2$ atmosphere to avoid oxidation with constant heating and cooling rates of 300 °C/
3.2.4. Sialon-based Green Phosphor

Green emitting phosphors can be applied for solid state lighting (SSL) with the excitation of a near ultraviolet (NUV) or a blue LED so that they turn radiation in the ranges 380–410 or 450–480 nm to light centered in the green region (520–565 nm). Blue-excited green-emitting phosphor with Sr₅Si₁₃Al₂O₃N₂1 host material doped with Eu²⁺ as an activator has been successfully developed by Yumi Fukuda et al. [214] through the typical procedure; mixing and firing of SrCO₃, Eu₂O₃, Si₃N₄, and AlN at temperatures ranging from 1700 to 1900°C for several hours under 0.7 MPa N₂ atmosphere. Highly efficient green-emitting Sr₆Si₂₅.₆Al₆.₄N₄₁.₆O₄.₄ phosphor was successfully prepared by Chunlei Zhao et al. [215] by gas pressure sintering, the internal and external quantum efficiencies of Sr₆Si₂₅.₆Al₆.₄N₄₁.₆O₄.₄ with 0.03 mol fractions of Eu²⁺ concentration and under 460 nm excitation are 85% and 64%, respectively. β-Sialon:Eu phosphor powders were dispersed into the ZnO–B₂O₃–BaO–Al₂O₃ glass matrix by Qiang-Qiang Zhu et al. [216] to fabricate green-emitting phosphor in glass materials for high-power blue laser lighting. Using the solid-state reaction, Ce³⁺, Tb³⁺-codoped β-sialon phosphors were prepared by Yang et al. [217] who indicated that the obtained phosphor has a broad excitation band that matches well with that of a UV LED chip, and adjusting the amount of Tb³⁺ ions can modulate the emission color of the obtained phosphor from blue to green due to the energy-transfer from Ce³⁺ and Tb³⁺ ions. Mixing and firing of Si₃N₄, AlN, CaCO₃, and Yb₂O₃ in a N₂ atmosphere has also been applied by Dierre et al. [218] to obtain several Ca- and Yb-doped sialon green phosphors. Jing Niu et al. [219] have applied a new method for preparation of Eu-doped β-Sialon green phosphors in which inexpensive raw materials as SiO₂, Al, and Si were used in addition to a small amount of NaCl as a diluent. The process has been applied under a relatively low nitrogen pressure and produced a single-phase, uniform, and rod-like particles with smallest thermal quenching of PL emission efficiency for high-power or white LEDs. Lihong Liu et al. [220] have used the solid-state reaction method to obtain Yb²⁺-activated Si₆₋ₓAl₂O₃N₈₋ₓ 0.05 ≤ z ≤ 2.3, 0.03 mol% ≤ Yb²⁺ ≤ 0.7 mol%) green phosphors, at 1900°C for 2 h under a nitrogen pressure of 1.0 MPa, indicating that β-sialon:Yb²⁺ phosphor exhibits green emission with an intensity controlled by the chemical composition of the host lattice and the concentration of Yb²⁺. Another green oxynitride phosphor, with a nominal composition of Eu₀.₀₀₂₉₆Si₀.₄₁₃₉₆Al₀.₀₁₃₃₆O₀.₀₀₄₄ N₀.₅₆₅₂₈ (β-Sialon:Eu²⁺), has been studied by Naoto Hirosaki et al. [221] who confirm that the prepared phosphor at 1900°C in a nitrogen atmosphere is superior to the commercially available green phosphors YAG:Ce³⁺ and ZnS:Cu,Al. This phosphor revealed, respectively, the internal and external quantum efficiencies of 70% and 61% at λₑₓ = 303 nm. The same green oxynitride phosphor was successfully prepared by Ryu et al. [222] using gas pressure sintering at 2000°C under a nitrogen pressure of 0.92 MPa, concluding that enhancing the Eu²⁺ concentration could control the emission bandwidths of the synthesized phosphor. A new route was used by Qi Wang et al. [223] to synthesize Eu-doped β-Sialon green phosphors through a self-propagation high-temperature synthesis (SHS) method that is a highly efficient and resulted in obtaining strong green-light emission that could be excited using UV or blue LED.

3.2.5. Sialon-based red phosphor

Red-emitting materials can be also applied for SSL upon excitation of a NUV or a blue LED; therefore, they must be able to turn efficiently radiation in the ranges 380–410 or 450–480 nm to light centered in the red region (625–740 nm). Such a conversion is not easy to achieve in an efficient way since the most common activator ions in many hosts are Eu³⁺ and Ce³⁺, which weakly emit in the red region. Host materials that can achieve efficient red emission based on 5d–4 f excitation and emission transitions should have (1) a strong ligand field, lowering the energy of the lowest (emitting) level belonging to the 4 fn-15d1 configuration and/or (2) the centroid of the 4 fn-15d1 configuration shifted to low energy (nephelauxetic effect, due to increased covalency). The aforementioned points occur only in a few hosts, as referred hereafter. The substitute is using activator ions that emit in the red region, exploiting intraconfigurational transitions. For instance, Mn⁴⁺ and Eu³⁺ provide luminescence through 4 f–4 f and 3d–3d transitions, respectively. Such transitions are intraconfigurational and parity-forbidden through the electric dipole mechanism; therefore they are weak, which is not suitable for phosphor performance [58]. Translucent Mg/α/β-sialon doped with different rare earth oxides (REOs), i.e. Pr₂O₃, Gd₂O₃, and Eu₂O₃, were fabricated by Joshi et al. [224] by hot press sintering, where Mg²⁺ cation acts as...
Table 3. Previous work details of different silion-based phosphors.

| Phosphor                  | Activator (% or mol%) | Color                      | Synth. | Excitation range (nm) | Emission λ (nm) |
|---------------------------|-----------------------|----------------------------|--------|------------------------|-----------------|
| Ca-o-Sialon:Eu²⁺ [203]   | Eu (7.5 mol%)         | Yellow                     | ↓      | 400 (UV/blue)          | 500–700         |
| Ca-o-Sialon:Eu²⁺ [204]   | Eu (7 mol%)           | Yellowish                   | ↑      | 450 (blue LED)         | 454             |
| Ca-o-Sialon:Eu²⁺ [205]   | Eu (3.75~22.5 mol%)   | Yellow                     | ↑      | 445 nm and 450         |                 |
| Ca-o-Sialon:Eu²⁺ [206]   | Eu (0.5~18 mol%)      | Orange                     | ↑      | 305 (UV)&350~500 (blue) | 585~600         |
| Ca-o-Sialon:Eu²⁺ [207]   | Eu (0.1~10 mol%)      | Yellow                     | ↑      | 325~460                | 566~580         |
| Ca-o-Sialon:Eu²⁺ [208]   | Eu (1 mol%)           | Yellow                     | ↑      | 225                    | 590             |
| Ca-o-Sialon:Eu²⁺ [209]   | Eu (5 mol%)           | Yellow                     | ↓      | 450                    | 460~700         |
| Ca-o-Sialon:Eu²⁺ [210]   | Eu (0~5 mol%)         | Yellow                     | ↑      | 438.6 to 449.6         | 585.4 to 601.4  |
| Ca-o-Sialon:Eu²⁺ [211]   | Eu (7 mol%)           | Yellow                     | ↓      | 550 to 650             |                 |
| Ca-o-Sialon:Eu²⁺ [212]   | Eu (7 mol%)           | Yellow                     | ↓      | 590                    | 460             |
| Ca-o-Sialon:Eu²⁺ [213]   | Eu (0~15 mol%)        | Yellow                     | ↑      | 380                    | 556~560         |
| β-Sialon:Eu²⁺ [214]      | Eu (2~11 mol%)        | Green                      | ↓      | 325 blue laser sources | 630~660         |
| Srβ-Sialon:Eu²⁺ [215]    | Eu (1~6 mol%)         | Green                      | ↑      | 460                    | 515             |
| β-Sialon:Ce³⁺,Tb³⁺ [217] | 3 mol% Ce³⁺, 3 mol% Tb³⁺ | Blue and Green            | ↑      | 345 for Ce, 277 for Tb & 345 for mix. | 450 for Ce, 542 for Tb & 542 for mix. |
| β-Sialon:Eu³⁺ [219]      | Eu (2 mol%)           | Green                      | ↑      | 405                    | 526~537         |
| β-Sialon:Yb³⁺ [220]      | Yb (0.03~0.7 mol%)    | Green                      | ↑      | 400                    | 540             |
| β-Sialon:Eu²⁺ [221]      | Eu (0.26 mol%)        | Green                      | ↑      | 280~480 (UV and Blue light) |                |
| β-Sialon:Eu²⁺ [222]      | Eu (0.65 mol%)        | Green                      | ↓      | 535                    |                 |
| β-Sialon:Eu²⁺ [223]      | Eu (3.5 mol%)         | Green                      | ↑      | 460                    | 525~540         |
| Srβ-Sialon:Eu²⁺ [214]    | Eu (8 mol%)           | Green                      | ↑      | 542 (UV)               | 300             |
| Ca-o-Sialon:Yb [218]     | Yb (0.5 mol%)         | Red                        | ↑      | 515                    | 365             |
| β-Sialon:Eu²⁺,Gd³⁺Pr³⁺ [224] | Eu⁺²⁺, Gd³⁺Pr³⁺ (0.5 wt.) | Red, blue, yellow and red for Gd³⁺, Eu²⁺ & Pr³⁺. | ↑      | 280 for Gd³⁺, 270 for Pr³⁺ & 460 for Eu²⁺ & 470 for Gd³⁺, 618 for Pr³⁺& 570 for Eu²⁺ |
| Sr₂Y₃Al₃O₁₂:Eu³⁺ [225]   | Eu (2, 7, 10, and 20 mol %) | Red | ↑ | 310~360 UV, 557~546 VIS, and 981 IR |
| β-Sialon:Pr³⁺ [226]      | Pr (1.6 mol%)         | Red                        | ↑      | 460                    |                 |

†: gas pressure sintering; ↑: solid-state reaction; ↓: combustion synthesis method; †+: Self-propagation high temperature; microwave sintering method; ↓: gas-reduction–nitridation.
4. Future prospect and conclusion

Based on this review, high-quality α- and β-sialon powders could be easily produced by carbothermal reduction-nitridation (CRN) using low-cost secondary resources, kaolin deposits and kaolinite. In addition, functionally graded sialon ceramics reinforced at their surfaces by α-sialon in order to take advantage of high hardness of α-sialon at the surface could be promising alternative candidates to the currently available silicon nitride-based blades that are used in the steam turbines used for power production from combined heat. What's more, the remarkable resistance to thermal shock and oxidation at elevated temperatures has made composite sialon a promising precursor for solar receiver applications [227]. More importantly, there are three RYG-sialon-based blue-excited phosphors with superior thermal stability and high quantum efficiency; Sr-containing sialon: Eu$^{2+}$ red-emitting phosphor; Ca-α-Sialon: Eu$^{2+}$ yellow-emitting phosphor [204, 228] and β-Sialon: Eu$^{2+}$ green-emitting phosphor [203]. Therefore, it is strongly recommended to combine these thermochemically stable RYG-sialon-based phosphors with the commercial blue LED chip to realize a warm wLED that will find a suitable application for general lighting and as a backlight in large-scale LCDs for flat-panel television sets or for in-vehicle use. Based on this review, the suggested packaging structure for a highly efficient sialon-based RYG-blue-pumped wLED could be plotted as shown in Figure 8, where blue-LED die could be stuck on the bottom of the metal cup. The RYG-sialon-based powder phosphors will be well-distributed in the wax and put inside the cup to transmit part of blue photons to red, yellow and green photons. A hemi-sphere silicon lens will be attached to the top surface of the phosphors in order to boost the light extraction.

Information about sialon phase properties and their potential applications, have been reviewed. Crystal structure, synthesis methods and final product properties and applications have been discussed to a greater extent. From the above study, the following concluded remarks can be drawn:

1. The incorporation of both alumina and alumina plus metal cation into silicon nitride to produce α and β sialons do not deteriorate the superior mechanical properties of the parent silicon nitrides because basically the same structure was reserved. Besides, the enhanced densification that resulted from the lower viscosities and eutectic temperatures of M-Si-Al-O-N liquids compared with

![Figure 8. Cross-sectional structure of the proposed blue-pumped RYG wLED.](image-url)
M-Si-O-N equivalents existing in silicon nitride-based materials was a very useful technologically. Consequently, sialon-based structural ceramics have already been successfully commercialized and established on the market.

(2) Sialon ceramics based on single β-phase exhibited the following properties: 88–92 HRA hardness of 88–92, 23–24 GPa microhardness, 400–500 MPa bending strength and 4.2–6.3 MPam0.5 crack resistance. The most important physico-mechanical properties of α- and β-sialon phases are summarized in Table 4 [4, 28, 29, 38, 229, 230]. The best bending strength and fracture toughness were exhibited by single β-phase Z = 0.5, and the highest oxidation resistance in the range of 800–1300°C was demonstrated in a single-β-sialon phase with a stoichiometric Si5.5Al2.5O5.5N12.5.

(3) Single-phased α-sialon-derived-ceramics revealed 3.5–4.8 MPa.m0.5 fracture toughness, 19–21 HV, and their resistance to oxidation depends on the stabilizing cation and its ionic size (Yb-α-sialon revealed the highest oxidation resistance).

(4) β-Sialon ceramics exhibit a quite high thermal conductivity value, and such value decreases linearly with rising α-sialon content in the double-phase sialon composite, following K = 12.46–0.043 f equation.

(5) In spite of the vast majority of commercially available structural sialon ceramics that are β-phase-derived products, α-sialons provide several desirable properties over β-sialons at elevated temperatures including higher maximum service temperature (1400 °C), higher creep resistance, and better thermal shock resistance. These valuable high-temperature characteristics of α-sialons will open the door wide for their potential use in a wide range of high-temperature, high-stress structural applications in corrosive environment.

(6) Sialon ceramics with specific characteristics can be potentially tailored by controlling both microstructure and phase composition of the final product.

**Table 4. Properties of α- and β-sialon-based ceramics.**

| Property                        | α-sialon | β-sialon |
|---------------------------------|----------|----------|
| Fracture toughness, MPa m0.5 [4] | 7–8      | 3–5      |
| Hardness, Hv, GPa [28, 29]      | 15–17    | 19–21    |
| RF-flexural strength, MPa       | 700–1100 | 350–500  |
| Maximum service temperature, °C | 1000     | 1400     |
| Microhardness, GPa [229]        | 23–24    | 23.5–32  |
| Bulk density, g/cm³ [230]       | 3.14–3.27| 3.25–3.45|
| Thermal conductivity, W/mK [38] | 13.5–19.7| 8.16–8.22|

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