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Yttria nettings by colloidal processing

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Abstract

Porous ceramic burners have been shown as a promising technology to produce heat and lighting by burning low calorific fuels like modern biomass. Among ceramics, yttria (Y_2O_3) presents considerable luminescent proprieties for gas burner technology. By colloidal processing of yttria, this work aims to produce luminescence ceramic nettings with potential to be used as gas burners. Processing parameters such as mean particle size, zeta potential and flow behavior were evaluated in order to prepare suitable suspensions for replica method. Yttria nanoparticles presented light emission with $\lambda = 550$ nm when being thermal stimulated at 150 °C. Besides, the nano sized powders $d_{50} = 113.8$ nm and specific surface area of 13.6 $m^2\ g^{-1}$ could be highly stabilized at pH 10.5. Suspensions with 30 vol% of solids, pH 10.5, 1 wt% of dispersant and 0.3 wt% of binder presented shear thinning behavior and thixotropy suitable for replica method. As a result, samples sintered at 1600 °C/1 h showed homogeneous morphology of struts and porous microstructure desirable for gas recirculation and burning process.

Keywords: Yttria; Ceramic processing; Porous ceramic; Gas burners; Luminescence

1. Introduction

Yttria (Y_2O_3) is one of the most important rare earth oxides. This structure is generally referred to as C-type. According to Hoekstra et al.[1] all the rare earths sesquioxides belong to this system such as Dy_2O_3, Th_2O_3, Ga_2O_3 and In_2O_3. Nevertheless, three Y_2O_3 polymorphs have been found. Gourlaouen et al.[2] and Srikanth et al. reported the monoclinic structure (B-type) at 997 °C under 2.0 GPa during plasma spray coating. Navrotsky et al.[3] showed that the C-type becomes fluorite type at 2308 °C and hexagonal A-type at 2325 °C. Quin et al.[4] observed structural changes from C-type to B-type for yttria nanoparticles smaller than 10 nm. Yttria has similar chemical and physical proprieties to other rare earth elements, thus is very used as matrix to compose luminescence materials. Wang et al.[5] reported that lighting emission of Y_2O_3:Eu^{3+} increased as a function of crystallite size and particle. Zhang et al.[6] observed a significant emission improvement for Y_2O_3:Eu^{3+} phosphors as synthesized by combustion reaction as well as sintering in vacuum. Goldburt et al.[7] described that Y_2O_3:Tb phosphors with particle diameter of 10 Å presented higher emission than those with 100 Å. Furthermore, Y_2O_3 is a potential material to be used in porous burners for lighting.

Barrer et al.[8] found out that lighting emission by gas combustion in porous components was more efficient rather than a free flame. The porous structure works as heat circulator, which improves flame speed, stability and low emission of CO_2. Thus, this technology fulfills requirements on lower pollution emissions (NO_x, CO), according to United Nations' Low Carbon plans.[9]

The processes commonly applied to produce porous ceramic components are sacrificial template, gel casting and replica.[10] The last one is very useful due to its applicability for any ceramic material dispersed in suspension. Further, the template can be any organic material to be burned out during thermal treatment. Several materials have been used such as wood,[11] carbon sponge,[12] polyurethane foam,[13] vegetal sponge,[14] coral mineral,[15] coral skeletal carbonate,[16] echinoid spines.[17]

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By replica components with complex shape can be produced. However, the ceramic suspension has to present a suitable rheological behavior, wherein viscosity plays an important role during the processing. High viscosity suspensions are not desired, seeing that they present much resistance to flow. As a result, they cannot recover and enter into cavities of porous template either. On the other hand, low viscosity suspensions cannot remain on the surface of the template, since they flow easily. Thus, the ceramic suspension has to be able to flow while is subjected of external force and has to present higher viscosity as static condition. This flow characteristic is reported as shear thinning behavior.[18] In addition, thermal treatment is extremely important. Controlling the heating rate and temperature slope the organic template can be burned out without disrupt the ceramic structure.

Nowadays, few studies about colloidal processing of yttria have been reported. One of the first papers reporting the isoelectric point (IEP) of yttria was done by Moreno et al.[19] In this study was reported that the isoelectric point of yttria particles was located at pH 8.5 and the highest zeta potential value was achieved at pH 11 ($\zeta = |50\,\text{mV}|$). Fuji et al.[20] evaluated the stability of yttria suspensions as a function of dispersant concentration and pH. As a result, yttria suspensions prepared with 1 wt% of polyacrylic ammonium acid (PAA) showed the lowest viscosity. Li et al.[21] showed that stable YAG ($Y_3Al_5O_{12}$) aqueous slurry presented a minimum viscosity in pH range between 9 and 11. Santos et al.[22] determined that high stable yttria suspensions ($\zeta = |56\,\text{mV}|$) could be prepared at pH 10 and with 1 wt% of PAA. Sonoda et al.[22] reported that Y-doped CeO_2 suspensions were more stable in acid pH range rather than alkaline. By colloidal processing of yttria since powder characterization and conditioning until rheological evaluation, this study aims to determine suitable processing parameters to produce luminescent ceramic nettings with potential for gas burner technology.

2. Experimental

Yttria powder (Y_2O_3) supplied by Johnson Matthey. Firstly, the powders were subjected of milling in atritor mill for 1 h based on prior work.[23] Powder characterization was performed by helium pycnometry (Pycnometer Micrometrics 1330); scanning electron microscopy (SEM, Philips XL30); X-ray fluorescence (XRF, Rigaku RIX 3000); X-ray diffraction (XRD, Rigaku Multiflex), with scanning at 1°/min, range from 10 to 80° (2θ), radiation Cu-kα; thermal gravimetric and thermal differential analyses (TGA/TDA, Setaram S60/38336), with a heating rate of 10 °C/min up to 1400 °C, in ambient atmosphere and having alumina as reference material; Photon Correlation Spectroscopy (PCS, ZetaPALS Analyzer, Brookhaven Instruments) to determine particle size distribution. For PCS, diluted aqueous suspensions with 0.001 vol% of particles were prepared at pH 10.5 by adding NaOH solution (0.5 M). Before measurements samples were homogenized in ultrasonic cleaner for 30 min (optimized time); specific surface area, by BET method (SSA, Micrometrics ASAP 2010). In addition to SSA, theoretical mean particle diameter (d_{BET}) was determined by BET equation (Eq. (1)), which considers particles having homogeneous morphology. Besides, based on d_{BET} result was calculated the agglomeration factor (F_{ag}) as shown in Eq. (2).

$$d_{BET} = \frac{6}{\rho_t . S_M}[\mu\text{m}] \quad (1)$$

where d_{BET} = theoretical mean particle diameter (μm); ρ_t = theoretical density (g cm^{-3}); S_M = specific surface area (m^2 g^{-1}).

$$F_{ag} = \frac{d_{50}}{d_{BET}} \quad (2)$$

where d_{50} = experimental mean particle diameter (μm); d_{BET} = theoretical mean particle diameter (μm).

The emitted luminescence of yttria particles was measured by a combined thermoluminescence reader (model Risø TL/OSL-DA-20) based on a heating system up to 700 °C and spectrometer (Ocean Optics, model QE65 Pro) with spectral sensibility from 200 to 950 nm. The samples were heated with a heating rate of 2 °C/s until 400 °C in room atmosphere. Afterwards, the samples were cooled by a nitrogen flow until room temperature.

The stability of powders in aqueous medium was evaluated by measuring the electrophoretic mobility of the particles and determining zeta potential (ζ) using Smoluchowski model (Eq. (3)) and zetameter based on light phase scatter analyzing (ZetaPALS, Brookhaven Instruments Corporation, USA). Stock suspensions with 0.5 g L^{-1} of solids were prepared, having NaCl 10^{-2} M as indifferent electrolyte. HCl and KOH solutions were used to shift pH of stock suspensions from acid to alkaline (pH 5.6–12). In order to compare the effectiveness of dispersant dosage on stability concentrations from 0.5 to 2 wt% of polyacrylic ammonium acid (PAA, Duramax D3005, Rohm and Haas Co.) were added in stock suspensions. Before measurements, all suspensions were homogenized in ultrasound cleaner for 2 min.

$$\xi = \frac{\mu_e \eta}{\varepsilon}[\text{mV}] \quad (3)$$

where ε = permittivity of liquid (J/V^2 m); η = viscosity of liquid (cP); μ_e = electrophoretic mobility of particles (μ s^{-1} V^{-1} cm).

Yttria aqueous suspensions were prepared varying solids loading from 15 to 33 vol% and using the following additives PAA, tetramethylammonium hydroxide (TMAH, Sigma–Aldrich) and carboxymethyl cellulose (CMC, Sigma–Aldrich) from 0.3 to 1 wt% (based on suspension weight). All suspensions were homogenized by ball milling for 24 h with alumina balls ($\varnothing_{balls}$ = 10 mm).

The flow behavior of suspensions was performed by a rheometer (Haake RS600, Thermo Scientific, Germany). The sensor system consisted in a double cone rotor and a stationary plate (DC60/1°). The characterization was carried out by flow curves in controlled rate mode (CR). Measurements were performed at 25 °C by increasing the shear rate from 0 to 1000 s^{-1} in 5 min, holding at 1000 s^{-1} for 2 min and returning to 0 s^{-1} in 5 min. For each CR run 200 points were measured.

For replica conformation a cotton-nylon netting (CNT) was selected as template considering its cells morphology distribution. Samples of CNT were immersed into yttria suspension; afterwards the excess of suspension was removed by squeezing