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# Reduce synthesis temperature and improve dispersion of YAG nanopowders based on the co-crystallization method



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#### ABSTRACT

Pure yttrium aluminum garnet (YAG) nanopowders were synthesized at 950 °C from the co-crystallization precursor of  $Y(NO_3)_3$ ·GH<sub>2</sub>O and  $Al(NO_3)_3$ ·GH<sub>2</sub>O (nitrate process). When 17 wt.% of  $Y(NO_3)_3$ ·GH<sub>2</sub>O was replaced by  $Y_2O_3$  nanopowders, so as to make up a three-layer core-shell structure of the precursor, the synthesis temperature was reduced to 850 °C ( $Y_2O_3$  process). Based on  $Y_2O_3$  process, further reducing the synthesis temperature to 700 °C was realized by adding polyacrylic acid (PAA, 50% M), which was used to shorten the distance of the metal ions and provide combustion heat (PAA process). TEM characterizations indicated that the powders produced through nitrate and  $Y_2O_3$  processes agglomerated, while the powders produced through PAA process were dispersed much better. The agglomerate size analysis results demonstrated that the powders produced through PAA process were with smaller agglomerate size and wider agglomerate size distribution than those through nitrate process or  $Y_2O_3$  process. And they were more likely to be sintered to YAG transparent ceramics.

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#### 1. Introduction

Yttrium aluminum garnet (YAG) is an excellent optical material due to its outstanding optical performance and high thermal stability. One of its most important applications is as laser host material. However, YAG single crystal with luminescence element is difficult to achieve large size and heavy doping, resulting in inability to output high power [1,2]. Since YAG transparent ceramic can overcome the defects of YAG single crystal [3,4], as well as easier and cheaper to produce, it has attracted much attention of researchers.

The sintering activity of YAG ceramic powders has great influence on the optical transmittance and the laser performance of YAG transparent ceramics. There are two source powders to produce YAG transparent ceramics: (1) Y<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub> as raw materials for solid-state reactive method. (2) YAG nanopowders produced by the wet-chemical methods. Conventional solid-state reactive method is easy, but it requires extensive heat treatment to eliminate the intermediate phases of YAM (Y<sub>4</sub>Al<sub>2</sub>O<sub>9</sub>) and YAP (YAlO<sub>3</sub>) [5,6]. Worse yet, many impurities are introduced during the repeated grinding and milling. To avoid these defects, wet-chemical methods have been used to produce phase-pure YAG nanopowders, such as co-precipitation technique [7,8], sol-gel process [9,10], hydrothermal (or solvothermal) treatment [11,12], combination of the above methods [13]. YAG nanopowders produced by the wet-chemical methods are more appropriate to produce YAG transparent ceramics owing to higher sintering activity. However, these wet-chemical methods either are difficult to control and time-consuming due to the needs of precise pH value [14] and aging duration [15,16], or demand high requirement for the equipment [17]. To get rid of the defects of these methods, a novel easy method through just calcining the aqueous solution of the raw materials has been used to synthesize MgAl<sub>2</sub>O<sub>4</sub> transparent ceramic nanopowders [18]. Key to this method is the close solubility of the salts in the solvent. Thus when the solvent is evaporated off, the metal salts are co-crystallized, resulting in metal ions mixed at an atomic level. Therefore, the synthesis temperature can lower to the wet-chemical level while the process is easier and yield is higher. So by analogy, if the solubility of an aluminum salt is close to that of a yttrium salt, or solubility of them is very high, YAG nanopowders can also be synthesized at a low temperature from the co-crystallization precursor, in which Y<sup>3+</sup> and Al<sup>3+</sup> have been mixed fully.

In this research, pure YAG nanopowders were synthesized through an easy method called co-crystallization method using the raw materials of  $Y(NO_3)_3$ · $GH_2O$  and  $Al(NO_3)_3$ · $GH_2O$ , as the solubility of them is high [19], seen in Table 1.  $Y_2O_3$  nanopowders and



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| Table T   |                                |
|---|--------------------------------|
| Solubility of Y(NO <sub>3</sub> ) <sub>3</sub> and Al(N | $O_3$ ) <sub>3</sub> in water. |

| Material  | Solubility (g/100 ml) |             |             |            |
|---|-----------------------|-------------|-------------|------------|
| _   | 0 °C                  | 20 °C       | 40 °C       | 60 °C      |
| Y(NO <sub>3</sub> ) <sub>3</sub><br>Al(NO <sub>3</sub> ) <sub>3</sub> | 93.1<br>60.0          | 123<br>73.9 | 163<br>88.7 | 200<br>106 |

polyacrylic acid (PAA) were selected to lower the synthesis temperature and improve dispersion. Effects of them were discussed in detail.

#### 2. Experimental procedures

YAG nanopowders were synthesized based on the co-crystallization method. The raw materials were  $Y(NO_3)_3.6H_2O$  (99.9%),  $Al(NO_3)_3.9H_2O$  (99%),  $Y_2O_3$  (40 nm, 99.99%) and PAA.  $Y_2O_3$  nanopowders were used to partly replace  $Y(NO_3)_3.6H_2O$  to lower YAG synthesis temperature, while PAA was used to overcome the agglomeration and lower the synthesis temperature further. (1) During nitrate process,  $Y(NO_3)_3.6H_2O$  and  $Al(NO_3)_3.9H_2O$  were weighted according to the stoichiometric ratio of  $Y_3Al_5O_{12}$  and dissolved in distilled water with the concentration of  $Al^{3+}$  being 1.65 M. The solution was stirred at a proper rotating speed by a magnetic stirrer at 100 °C until it became too sticky for the magnetic stirrer to rotate. Then the sticky mixture (YAG precursor) was put into a crucible and calcined at different temperatures for 3 h. (11) During  $Y_2O_3$  process, 17 wt.% of  $Y(NO_3)_3.6H_2O$  was replaced by  $Y_2O_3$  nanopowders. Later process was the same as above. (111) During PAA process, PAA which was 50 wt.% of  $Y(NO_3)_3.6H_2O$ ,  $Al(NO_3)_3.9H_2O$  and  $Y_2O_3$  was added into the solution based on  $Y_2O_3$  process. Later process was still unchanged.

Crystal structure of the powders was examined by X-ray diffraction(XRD, Rigaku Dmax-rC, Japan) using Cu K $\alpha$  radiation in the range of  $2\theta$  = 10–65° with a scanning speed of 10°/min, while the powders used for particle size calculating by Scherrer formula were scanned at the speed of 2°/min again. Morphology was characterized by transmission electron microscope (TEM, Tecnai G2 20, Netherlands) with accelerating voltage of 200 kV. The agglomerate size was measured by laser particle size analyzer (Mastersizer 3000, England). Thermal gravimetric analysis on the nitrates was carried out by thermogravimetric analyzer and differential scanning calorimeter (TGA/DSC, Mettler-Toledo 1, Switzerland) with the heating rate of 10°C/min.

#### 3. Results and discussions

#### 3.1. The effect of synthesis temperatures through nitrate process

Fig. 1 shows the TG curves of  $Y(NO_3)_3$  and  $AI(NO_3)_3$  as a function of temperature. It can be seen that the mass losses of the two salts are very limited above 500 °C, indicating  $Y(NO_3)_3$  and  $AI(NO_3)_3$ almost have decomposed to the precursors of  $Y_2O_3$  and  $AI_2O_3$ respectively. The result is in agreement with the study made by



Fig. 1. TG curves of Y(NO<sub>3</sub>)<sub>3</sub> and Al(NO<sub>3</sub>)<sub>3</sub>.

Ref. [20]. The low decomposition temperatures of  $Y(NO_3)_3$  and  $Al(NO_3)_3$  is favor of a low synthesis temperature of YAG, as the active precursors of  $Y_2O_3$  and  $Al_2O_3$  are readily to react with each other.

Fig. 2 shows the XRD patterns of the powders calcined from 850 °C to 1100 °C for 3 h through nitrate process. The powders are amorphous when calcined at 850 °C. As the temperature increases to 900 °C, YAG is the dominant phase with small amount of secondary phase of YAM. Pure YAG is synthesized until 950 °C. From 950 °C to 1100 °C none change occurs except for sharpening of the diffraction peaks. The result indicates that the crystallinity of the powders is improved gradually.

Fig. 3 shows TEM micrographs of the powders calcined at 500 °C, 850 °C, 950 °C, 1000 °C for 3 h through nitrate process respectively. It can be seen that the particle sizes are about 10 nm. 20-30 nm. 30-40 nm when calcined at 500 °C. 850 °C. 950 °C respectively, indicating the particle size increases as the calcination temperature increases. However, the powders are dispersed badly. It is hard to find a single particle when the calcination temperature is higher than 850 °C. When calcined at 500 °C, the particles of  $Y_2O_3$  and  $Al_2O_3$  precursors cluster together, leaving little space between them, seen in Fig. 3(a). Therefore, slight agglomeration has been formed below 500 °C already. The agglomeration is caused by the big surface tension, capillary force and hydrogen bond of the crystal water contained in the nitrates [21], as the crystal water cannot be removed at 200 °C [22,23]. And the agglomeration will be aggravated as the calcination temperature increases. From 500 °C to 1000 °C, the necklike connections between the particles become more evident, demonstrating the surface diffusion and grain boundary diffusion are easy to be achieved among the agglomerated particles.

#### 3.2. The effect of Y<sub>2</sub>O<sub>3</sub> nanopowders through Y<sub>2</sub>O<sub>3</sub> process

As the synthesis temperature is a little high through nitrate process,  $Y_2O_3$  nanopowders were added as the raw materials to lower the synthesis temperature. The XRD patterns of the powders calcined at 800 °C, 850 °C, 950 °C for 3 h through  $Y_2O_3$  process are shown in Fig. 4(a–c). It can be seen that the powders are amorphous at 800 °C, and pure YAG is synthesized at 850 °C. The synthesis temperature has been reduced by 100 °C compared with nitrate process. Difference between the diffraction peak intensity of the powders calcined at 950 °C through nitrate and  $Y_2O_3$  process is also shown in Fig. 4(c and d). The stronger diffraction peak



Fig. 2. XRD patterns of the powders calcined at different temperatures for 3 h through nitrate process.



Fig. 3. TEM micrographs of the powders calcined at different temperatures for 3 h through nitrate process (a) 500 °C, (b) 850 °C, (c) 950 °C and (d) 1000 °C.



**Fig. 4.** XRD patterns of the powders calcined at different temperatures for 3 h through  $Y_2O_3$  process and nitrate process (a) 800 °C through  $Y_2O_3$  process, (b) 850 °C through  $Y_2O_3$  process, (c) 950 °C through  $Y_2O_3$  process and (d) 950 °C through nitrate process.

intensity indicates the better crystallinity of the powders produced through Y<sub>2</sub>O<sub>3</sub> process at 950 °C.

The reason of lowering the synthesis temperature via adding  $Y_2O_3$  is as follow. During the evaporation process,  $Al(NO_3)_3$  crystallizes earlier, for solubility of  $Al(NO_3)_3$  is smaller than that of  $Y(NO_3)_3$ . So segregation between  $Al(NO_3)_3$  and  $Y(NO_3)_3$  occurs, resulting in difficulties in mass transfer between  $Y^{3+}$  and  $Al^{3+}$  during the high temperature, so as to raise the synthesis temperature. However, when  $Y_2O_3$  nanopowders are dispersed in the solution uniformly, they provide heterogeneous nuclei for  $Al(NO_3)_3$  to crystallize on, then the later crystallized  $Y(NO_3)_3$  adheres on  $Al(NO_3)_3$  again. In this manner, the three materials make up a three-layer core-shell structure, shown in Fig. 5. And the distance between  $Y^{3+}$  and  $Al^{3+}$  is shortened by the three-layer core-shell structure. As a consequence, mass transfer is promoted when calcined at high temperature and the synthesis temperature is reduced.

Fig. 6 shows TEM micrographs of YAG nanopowders calcined at 850 °C, 950 °C through  $Y_2O_3$  process. The particle sizes are 20–40 nm, 30–50 nm when calcined at 850 °C, 950 °C respectively, bigger than those through nitrate process. And the particles agglomerate again by the same mechanism as nitrate process. However, the agglomeration is weakened when calcined at the same temperature. This is because the crystallinity of the powders calcined at 850 °C is improved through  $Y_2O_3$  process, the activity or the surface energy of the particles is lowered, resulting in less potential of clustering together and weaker agglomeration.



Fig. 5. Model of three-layer core-shell structure formed by Y<sub>2</sub>O<sub>3</sub>, Al(NO<sub>3</sub>)<sub>3</sub>, Y(NO<sub>3</sub>)<sub>3</sub>.



Fig. 6. TEM micrographs of YAG powders calcined at different temperatures for 3 h through Y2O3 process (a) 850 °C and (b) 950 °C.

#### 3.3. The effect of PAA through PAA process

To improve the dispersion and lower the synthesized temperature further, PAA is added in as the raw material based on  $Y_2O_3$ process. In this process, it plays as a chelating agent, as it can react with most high valence metal ions at a certain temperature [24]. So by stirring at 100 °C, PAA can react with  $Y^{3+}/A^{3+}$  as Eq. (1):  $Y_2O_3$  process. And this is the lowest temperature to synthesize YAG without the use of autoclave. The so low synthesis temperature can be explained in two aspects: (1) The effect of  $Y_2O_3$  nanopowders. As electronegativity of Al is higher than that of Y, the formation speed of  $-COOAI_{1/3}$  is faster than that of  $-COOY_{1/3}$ . Therefore, segregation between  $Y^{3+}$  and  $AI^{3+}$  takes place in polymeric chelate. Similar to  $Y_2O_3$  process, a three-layer core-shell structure is again



M stands for Y/Al. YAG precursor has been evolved to polymeric chelate of  $Y^{3+}/Al^{3+}$  during PAA process.

Fig. 7 shows the XRD patterns of the powders calcined at 650 °C, 700 °C, 800 °C for 3 h through PAA process. As can be seen from it, pure YAG is synthesized at 700 °C, 150 °C lower than that through



**Fig. 7.** XRD patterns of the powders calcined at different temperatures for 3 h through PAA process.

formed by  $Y_2O_3$  nanopowders, aluminum chelate and yttrium chelate. (2) The properties of PAA. The close distance of -COO- in PAA results in closer distance of -COOAl<sub>1/3</sub> and -COOY<sub>1/3</sub>, so mass transfer between Al<sup>3+</sup> and Y<sup>3+</sup> at high temperature is promoted again. Moreover, PAA provides combustion heat required to synthesize YAG [25]. As a consequence, the synthesis temperature is reduced again.

Fig. 8 shows TEM micrographs of YAG nanopowders calcined at 850 °C, 950 °C through PAA process. The particle sizes are 30–50 nm, 40–70 nm when calcined at 850 °C, 950 °C respectively. The sizes are larger than those through the other two methods. And the particles show much better dispersion, reflecting that PAA has significant effect on dispersion. The good dispersion is due to insolubility of polymeric chelate of  $Y^{3+}/Al^{3+}$ . So water can be removed out easily at a low temperature, then hard agglomeration is greatly weakened.

Fig. 9 shows the photographs of powders calcined at 850 °C for 3 h through PAA process and  $Y_2O_3$  process. The powders form small granules through PAA process, while they form flakes through  $Y_2O_3$  process. The macro-figure also indicates PAA can improve dispersion.

#### 3.4. Comparison of the powders produced through the three processes

Table 2 shows the particle sizes and agglomerate sizes of the powders produced through nitrate process at 950 °C (P1),  $Y_2O_3$  process at 850 °C (P2) and PAA process at 700 °C (P3). The mean



Fig. 8. TEM micrographs of YAG powders calcined at different temperatures for 3 h through PAA process (a) 850 °C and (b) 950 °C.



Fig. 9. Photographs of powders calcined at 850 °C through different processes for 3 h (a) PAA process and (b) Y<sub>2</sub>O<sub>3</sub> process.

#### Table 2

Particle sizes and agglomerate sizes of YAG powders produced through nitrate process at 950 °C (P1),  $Y_2O_3$  process at 850 °C (P2) and PAA process at 700 °C (P3).

| Powder | $D_{\rm XRD}$ ( $\mu m$ ) | <i>D</i> <sub>TEM</sub> ( μm) | D <sub>50</sub> ( μm) |
|--------|---------------------------|-------------------------------|-----------------------|
| P1     | 0.0404                    | 0.030-0.040                   | 50.0                  |
| P2     | 0.0356                    | 0.020-0.040                   | 33.4                  |
| P3     | 0.0174                    | -                             | 8.19                  |
|        |                           |                               |                       |

primary size particle calculated from the XRD peak profile is defined as  $D_{XRD}$ . The mean crystallite size estimated from the TEM photograph is denoted as  $D_{\text{TEM}}$ . And the mean agglomerate size  $D_{50}$  is the median diameter determined from the agglomerate size distribution measured by the laser particle size analyzer. D<sub>TEM</sub> of the powders through PAA process at 700 °C is not given here, as they have not been tested by TEM. The  $D_{\text{TEM}}$ 's of P1and P2 almost agree with the respective values of  $D_{XRD}$  within error, while the agglomerate sizes  $D_{50}$  are much bigger than the particle sizes  $D_{XRD}$ . The values of  $D_{50}/D_{XRD}$  of P1, P2 and P3 are 1237,938 and 470 respectively, indicating the agglomeration is weakened by these processes gradually, consistent with the TEM results. According to WH Rhodes, agglomerate limits attainable green density and final ceramic density [26]. The big size agglomerates lead to big pores in the compact. So the green density is limited. And the dense agglomerates can readily become single grains at the initial stage of sintering, leaving cracks between the surrounding grains, which will evolve to isolated pores at the final stage of sintering. As a result, the final density is limited. What's more, the mechanism increases with the increasing agglomerate size. So P3 may be most beneficial for sintering while P1 worst.



**Fig. 10.** Agglomerate size distributions of the powders through nitrate process at 950 °C (P1),Y<sub>2</sub>O<sub>3</sub> process at 850 °C (P2) and PAA process at 700 °C (P3).

Fig. 10 shows the agglomerate size distributions of the three powders. The agglomerate sizes of P1and P2 range from 0.48  $\mu$ m to 115  $\mu$ m, while that of P3 ranges from 0.35  $\mu$ m to 105  $\mu$ m. The double peaks in profile of P3 indicate the agglomerate sizes are mainly distributed in two ranges: 1  $\mu$ m and 20  $\mu$ m. The more smooth profile of P3 indicates the agglomerate size distribution is wider than that of P1 and P2, as the agglomerate sizes of P1, P2 are mainly distributed in the narrow larger-size area. Since the fine particles or small agglomerates can fill the gaps in the

compacter, the green density of powders with wider agglomerate size distribution will be increased, leading to enhanced densification of the compacts at the initial stage of sintering [27].

#### 4. Conclusion

Pure YAG nanopowders were synthesized at 950 °C through an easy co-crystallization method. The synthesis temperature was lowered by 100 °C via a three-layer core–shell structure of YAG precursor. The powders produced through the two methods were agglomerated heavily due to the big surface tension, capillary force and hydrogen bond of the crystal water. So they might not suitable for compacters with high green density and ceramics with fine grains. The hard agglomeration was weakened by adding PAA (50% M) along with the synthesis temperature reduced to 700 °C based on the three-layer core–shell structure. The smaller agglomerate size with wider wide size distribution of the powders produced through this process showed more possibility to be sintered to transparent YAG ceramics.

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#### References

- C. Belouet, About the crystalline perfection of Nd-doped YAG single crystals, J. Cryst. Growth 15 (1972) 188–194.
- [2] C.M. Wong, S.R. Rotman, C. Warde, Optical studies of cerium doped yttrium aluminum garnet single crystals, Appl. Phys. Lett. 44 (1984) 1038–1040.
- [3] S.F. Wang, J. Zhang, D.W. Luo, et al., Transparent ceramics: processing, materials and applications, Prog. Solid State Chem. 41 (2013) 20–54.
- [4] A. Ikesue, Y.L. Aung, T. Yoda, et al., Fabrication and laser performance of polycrystal and single crystal Nd: YAG by advanced ceramic processing, Opt. Mater. 29 (2007) 1289–1294.
- [5] A. Ikesue, I. Furusato, Fabrication of polycrystalline, transparent YAG ceramics
- by a solid-state reaction method, J. Am. Ceram. Soc. 78 (1995) 225–228.
- [6] Y.S. Wu, J. Li, F.G. Qiu, et al., Fabrication of transparent Yb, Cr: YAG ceramics by a solid-state reaction method, Ceram. Int. 32 (2006) 785–788.
- [7] J.G. Li, T. Ikegami, J.H. Lee, et al., Co-precipitation synthesis and sintering of yttrium aluminum garnet (YAG) powders: the effect of precipitant, J. Eur. Ceram. Soc. 20 (2000) 2395–2405.

- [8] X.X. Li, W.J. Wang, Preparation of uniformly dispersed YAG ultra fine powders by co-precipitation method with SDS treatment, Powder Technol. 196 (2009) 26–29.
- [9] Q.Q. Zhu, W.W. Hu, L.C. Ju, et al., Synthesis of Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub>:Eu<sup>2+</sup> phosphor by a facile hydrogen iodide-assisted sol-gel method, J. Am. Ceram. Soc. 96 (2013) 701–703.
- [10] M. Zarzecka, M.M. Bucko, J. Brzezinska Miecznik, K. Haberko, YAG powder synthesis by the modified citrate process, J. Eur. Ceram. Soc. 27 (2007) 593– 597.
- [11] A. Cabanas, J. Li, P. Blood, et al., Synthesis of nanoparticulate yttrium aluminum garnet in supercritical water–ethanol mixtures, J. Supercrit. Fluids 40 (2007) 284–292.
- [12] X. Li, H. Liu, J.Y. Wang, et al., Production of nanosized YAG powders with spherical morphology and nonaggregation via a solvothermal method, J. Am. Ceram. Soc. 87 (2004) 2288–2290.
- [13] S.K. Yang, W.X. Que, J. Chen, et al., Nd:YAG nano-crystalline powders derived by combining co-precipitation method with citric acid treatment, Ceram. Int. 38 (2012) 3185–3189.
- [14] C. Marlot, E. Barraud, S.L. Gallet, et al., Synthesis of YAG nanopowder by the coprecipitation method: influence of PH and study of the reaction mechanisms, J. Solid State Chem. 191 (2012) 114–120.
- [15] X.L. Zhang, D. Liu, Y.H. Sang, et al., Effects of aging on the characteristics of Nd: YAG nano-powders, J. Alloys Comp. 502 (2010) 206–210.
- [16] H. Gong, D.Y. Tang, H. Huang, et al., Crystallization kinetics and characterization of nanosized Nd: YAG by a modified sol-gel combustion process, J. Cryst. Growth 362 (2013) 52–57.
- [17] M. Inoue, H. Otsu, H. Kominaml, et al., Synthesis of yttrium aluminum garnet by the glycothermal method, J. Am. Ceram. Soc. 74 (1991) 1452–1454.
- [18] T.C. Lu, X.H. Chang, J.Q. Qi, et al., Low-temperature high-pressure preparation of transparent nanocrystalline MgAl<sub>2</sub>O<sub>4</sub> ceramics, Appl. Phys. Lett. 88 (2006) 213120–213203.
- [19] J.A. Dean, Lange's Handbook of Chemistry Section 5, in: Physical Properties, World Publishing Company, Beijing, 2003, pp. 639–662.
  [20] Y.H. Sang, H. Liu, Y.H. Lv, et al., Yttrium aluminum garnet nanoparticles
- [20] Y.H. Sang, H. Liu, Y.H. Lv, et al., Yttrium aluminum garnet nanoparticles synthesized by nitrate decomposition and their low temperature densification behavior, J. Alloys Comp. 490 (2010) 459–462.
- [21] A. Maskara, D.M. Smith, Agglomeration during the drying of fine silica powders, Part II: the role of particle solubility, J. Am. Ceram. Soc. 80 (1997) 1715-1722.
- [22] P. Melnikov, V.A. Nascimento, I.V. Arkhangelsky, et al., Thermal decomposition mechanism of aluminum nitrate octahydrate and characterization of intermediate products by the technique of computerized modeling, J. Therm. Anal. Calorim. 111 (2013) 543–548.
- [23] P. Melnikov, V.A. Nascimento, L.Z. Consolo, et al., Mechanism of thermal decomposition of yttrium nitrate hexahydrate, Y(NO<sub>3</sub>)<sub>3</sub> 6H<sub>2</sub>O and modeling of intermediate oxynitrates, J. Therm. Anal. Calorim. 111 (2013) 115–119.
- [24] H. Taguchi, D. Matsuda, M. Naga, Synthesis of LaMn0<sub>3</sub> using poly(acrylic acid), J. Mater. Sci. Lett. 12 (1993) 891–893.
- [25] Y.K. Sun, I.H. Oh, S.A. Hong, Synthesis of ultrafine LiCoO<sub>2</sub> powders by the solgel method, J. Mater. Sci. 31 (1996) 3617–3621.
- [26] W.H. Rhodes, Agglomerate and particle size effects on sintering yttriastabilized zirconia, J. Am. Ceram. Soc. 64 (1981) 19–22.
- [27] J. Ma, L.C. Lim, Effect of particle size distribution on sintering of agglomeratefree submicron alumina powder compacts, J. Eur. Ceram. Soc. 22 (2002) 2197– 2208.