

# Combustion synthesis: an update

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## Abstract

Combustion synthesis has emerged as a facile and economically viable technique for the preparation of advanced ceramics, catalysts and nanomaterials. Recent innovations in the combustion and processing parameters have resulted in a better understanding of combustion phenomena and control of microstructure and property of the products.

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## 1. Introduction

Combustion synthesis (CS) [1] has emerged as an important technique for the synthesis and processing of advanced ceramics (structural and functional), catalysts, composites, alloys, intermetallics and nanomaterials. In CS, the exothermicity of the redox (reduction–oxidation or electron transfer) chemical reaction is used to produce useful materials [\*2]. Depending upon the nature of reactants: elements or compounds (solid, liquid or gas); and the exothermicity (adiabatic temperature,  $T_{ad}$ ), CS is described as: self-propagating high temperature synthesis (SHS); low-temperature combustion synthesis (LCS), solution combustion synthesis (SCS), gel-combustion, sol–gel combustion, emulsion combustion, volume combustion (thermal explosion), etc. Combustion synthesis processes are characterised by high-temperatures, fast heating rates and short reaction times. These features make CS an attractive method for the manufacture of technologically useful materials at lower costs compared to conventional ceramic processes. Some other advantages of CS are:

- (i) Use of relatively simple equipment
- (ii) Formation of high-purity products
- (iii) Stabilization of metastable phases and
- (iv) Formation of virtually any size and shape products

The literature on CS is vast and most of the materials prepared and their applications have been summarized in

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recent publications [\*2,\*\*3,\*4,\*\*5]. The popularity of the method is reflected in the large number of publications on CS appearing in the Materials Science journals and a decade of publication of the *International Journal of Self-propagating High Temperature Synthesis* (Allerton Press, New York).

In our earlier review on CS [1], we discussed the preparation of a wide range of technologically important materials by SHS, solid state metathesis (SSM), thermite type SHS, gas-phase (flame) synthesis as well as by combustion of redox compounds and mixtures. Currently, we discuss the recent developments in the field with special emphasis on the preparation of ‘Catalysts’ and ‘Nanomaterials’ by solid state combustion (SSC) and solution combustion (SC). Gas phase CS has not been covered.

## 2. Solid state combustion

In solid state combustion (SSC), initial reactants, intermediates and final products are all in the solid state. Combustion of solid reactants can occur in two modes: (i) linear or self-propagating, high temperature synthesis (SHS) and (ii) bulk or volume combustion synthesis (VCS). In both the cases, the reactants are pressed into a pellet, typically cylindrical in shape. The pellet is then ignited by an external source (e.g. tungsten coil, laser or microwave) either locally (SHS) or uniformly (VCS), which initiates an exothermic reaction. For SHS, the reaction should be highly exothermic ( $\Delta H \sim 40 \text{ kcal mol}^{-1}$  or  $16\,800 \text{ J mol}^{-1}$ ) and the rate of heat generation must be

greater than the heat dissipated; otherwise the reaction will be quenched and will not be self-propagating. The characteristic feature of the SHS mode is that, following local initiation, the hot combustion wave (2000–4000 K) passes through the heterogeneous mixture of reactants yielding the desired condensed product. In VCS (thermal explosion), the pellet is heated uniformly in a controlled manner until the reaction occurs simultaneously throughout the volume. This mode of synthesis is suitable for weakly exothermic reactions that require activation by preheating or electric field.

Solid state combustion is used in the synthesis of a variety of advanced materials. A general article, 'Forms from fire' by Varma [\*4] illustrates the simplicity of SSC process for preparing binary refractory materials, intermetallics, and alloys. The materials prepared and their applications are: aluminides—AlNi (aerospace and turbine material); borides—TiB<sub>2</sub> (abrasives, cutting tool); carbides—SiC, TiC (abrasives and cutting tool); chalcogenides—MoS<sub>2</sub> (high temperature lubricant); hydrides—MgH<sub>2</sub> (hydrogen storage); nitrides—Si<sub>3</sub>N<sub>4</sub> (ceramic engine parts); oxides—La<sub>0.8</sub>Sr<sub>0.2</sub>CrO<sub>3</sub> (fuel cell interconnect); phosphides—GaP (semiconductor); silicides—MoSi<sub>2</sub> (high temperature heating element) and titanates—TiNi (shape memory alloy). A review article on 'Combustion synthesis of advanced materials: principles and applications' [\*\*5], deals with the theory and modeling of SHS reactions based on experimental observations using Time Resolved X-ray Diffraction (TRXRD) and high speed video microscopy. These studies have helped in not only promoting a better understanding of the SSC phenomenon but also in producing tailor-made products e.g. in the formation of titanium silicides (Ti<sub>3</sub>Si<sub>5</sub>, TiSi<sub>2</sub>) of uniform microstructure by carrying out CS with a high density sample [\*4,\*\*5].

Recent innovations in the processing of materials involve carrying out SSC in the presence of applied electric and magnetic fields and gravity. Field activated combustion synthesis (FACS) has been employed by Munir and colleagues [6–11] for the synthesis of low enthalpy materials such as metal silicides (V, Cr, W, Nb, Ta), intermetallics (Fe–Al), functionally graded materials (Ti–C–Cu), composites (TiB<sub>2</sub>–TiAl<sub>3</sub>) and SOFC anode (Ni/YSZ). The main limitations of FACS is that the process cannot be used for reactions that form materials with high conductivity (Nb<sub>5</sub>Si<sub>3</sub>) as the current density in the heating zone decreases leading to extinction of the wave.

Similarly, Parkin and his associates have carried out extensive studies on the preparation of soft and hard ferrites by SSC of metal–metal oxide or peroxides in the presence of an external magnetic field [\*\*3,12,13]. It was observed that the velocity of the combustion reaction increases with the application of a magnetic field and the magnetic properties of the products also improve. For example, barium hexaferrite formed in the presence of a magnetic field has greater coercivity and remanence com-

pared to materials prepared in the absence of a field. Similarly, formation of tetragonal CuFe<sub>2</sub>O<sub>4</sub> is favoured in the presence of a magnetic field compared to the formation of cubic CuFe<sub>2</sub>O<sub>4</sub>, which occurs preferentially in the absence of a magnetic field.

Combustion synthesis of TiC and TiC–Al<sub>2</sub>O<sub>3</sub>–Al, TiB<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–Al, ZrB<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–Al, B<sub>4</sub>C–Al<sub>2</sub>O<sub>3</sub> composites has been studied under microgravity [\*\*5]. These studies show that gravity significantly influences the CS and more uniform microstructured products are formed. This also opens the possibility of production of nanophase materials with high porosity. Varma et al. [14] have investigated the combustion synthesis of Ni–Al-based materials reinforced by TiB<sub>2</sub> particles under both terrestrial and microgravity conditions and they have found that microgravity leads to a decrease in the average TiB<sub>2</sub> size. In addition, an overall decrease in microstructural transformation rates under microgravity was observed.

Solid state combustion has been extensively used to prepare a variety of catalysts e.g. oxynitrides (honeycomb support for noble metals); complex cuprates, LnMCu<sub>n-δ</sub>, Ln=Y or La, M=Ca, Ba or Sr (ethylene synthesis); LnCaB<sub>6</sub> (oxidation of methane to ethylene); Fe–Al alloys (ammonia synthesis); modified spinel and Fe–Cr oxides (pyrolysis of diesel fuel) [\*\*3,15]. Other technologically useful materials prepared by SSC are: solid oxide fuel cell materials: Sr and Ga doped LaFeO<sub>3</sub> [16], La<sub>0.84</sub>Sr<sub>0.16</sub>CrO<sub>3</sub> [17], La<sub>0.2</sub>Sr<sub>0.8</sub>Cr<sub>0.2</sub>Fe<sub>0.8</sub>O<sub>3-x</sub> [18], La<sub>1-x</sub>Sr<sub>x</sub>MnO<sub>3</sub> [19]; the hydrogen storage alloy, Mg<sub>2</sub>NiH<sub>4</sub> [20] and porous NiTi (biomedical implant material) [21]. Interestingly, a number of nanosize SiC, AlN and Si<sub>3</sub>N<sub>4</sub> materials have been prepared by SSC of precursors containing volatile ammonium halides [22] and microwave initiation [23].

### 3. Solution combustion

The solution combustion (SC) method of preparing oxide materials is a fairly recent development compared to SSC or SHS techniques described above. Today, SC is being used all over the world to prepare oxide materials for a variety of applications. During the short span (15 years) of SC synthesis history, hundreds of papers on SC of oxides have been published, many from the author's laboratory.

In our previous review [1], we presented a list of oxide materials prepared by rapidly heating aqueous solutions containing stoichiometric amounts of respective metal nitrate (oxidiser) and fuels like urea/hydrazides (carbohydrazide (CH), oxalyl dihydrazide (ODH), malonic acid dihydrazide (MDH), tetra formal tris azine (TFTA), etc.). A wide range of technologically useful oxides (alumina to zirconia) were prepared with interesting magnetic, dielectric, electrical, mechanical, catalytic, luminescent and optical properties. It was possible to prepare oxide materials with desired composition, structure (spinel, perovskite,

garnets, etc.) by SC. Interestingly, some of the fuels used were found to be specific for a particular class of oxides e.g. urea—for alumina and related oxides; CH—for zirconia and related oxides; ODH—for  $\text{Fe}_2\text{O}_3$  and ferrites, TFTA—for  $\text{TiO}_2$  and related oxides; glycine—for chromium and related oxides, etc.

All these fuels serve two purposes:

- They are the source of C and H, which on combustion form  $\text{CO}_2$  and  $\text{H}_2\text{O}$  and liberate heat.
- They form complexes with the metal ions facilitating homogeneous mixing of the cations in solution.

The exothermicity ( $T_{\text{ad}}$ ) of the redox reaction varies from 1000 to 1800 K. Depending upon the fuel used, the nature of combustion differs from flaming to non-flaming (smouldering).

The oxide materials prepared and investigated during the

review period have been listed in Table 1 along with the fuels used and their applications. Not surprisingly, urea occupies the centre stage, probably due to its ready availability and high exothermicity. Most of the oxides prepared by the urea method are alumina-based e.g.  $\alpha\text{-Al}_2\text{O}_3$  products [\*24]. Another development in alumina synthesis by the urea process is the preparation of nanosize  $\alpha\text{-Al}_2\text{O}_3$  by microwave initiated SC [25]. The process yields nanosize alumina, since combustion is accompanied by controlled release of gases and dissipation of heat. The ease of doping metal ion in oxides by SC has not only yielded ZTA [26], but has also resulted in the facile synthesis of metal and alloy doped alumina, aluminates [27–29], pigments [30] and phosphors [31,32]. Combustion of aluminium nitrate-urea in the presence of halide salts of Pt, Pd, Ag and Au yielded uniformly dispersed  $\text{M}/\text{Al}_2\text{O}_3$  composites. These exhibit better catalytic properties towards oxidation of CO and hydrocarbon and

Table 1  
Oxide materials prepared by solution combustion

Material	Fuel	Particle size	Application	References
$\text{Al}_2\text{O}_3$	U	4 $\mu\text{m}$	Abrasive	[*24]
$\text{Al}_2\text{O}_3$	U	19 nm	Catalyst support	[25]
$\text{Al}_2\text{O}_3\text{-ZrO}_2$	U	20–45 nm	Cutting tool	[26]
$\text{MAl}_2\text{O}_4$ (M=Mn and Zn)	MA+U/CH/ ODH/GLY	15–28 nm	Catalytic support	[27]
$\text{MgAl}_2\text{O}_4$	U	13–20 nm	Structural material	[28]
$\text{M}/\text{MgAl}_2\text{O}_4$ , M=Fe–Co/Ni	U	10 nm	Catalyst	[29]
$\text{Co}^{2+}/\text{Al}_2\text{O}_3$	U	0.2–0.3 $\mu\text{m}$	Pigment	[30]
$\text{Eu}^{3+}/\text{Y}_3\text{Al}_5\text{O}_{12}$	U	60–90 nm	Red phosphor	[31]
$\text{Ce}_{1-x}\text{Tb}_x\text{MgAl}_{11}\text{O}_{19}$	CH	10–20 $\mu\text{m}$	Green phosphor	[32]
$\text{M}/\text{Al}_2\text{O}_3$ , M=Pt, Pd, Ag and Au	U	7–10 nm	Catalyst	[33,34]
$\text{Pd}/\text{Al}_2\text{O}_3$	U	10–18 nm	Catalyst	[35]
$\text{CeO}_2\text{-ZrO}_2$	ODH	18 nm	Oxygen storage capacitor	[36]
	GLY	100 $\mu\text{m}$	Oxygen storage capacitor	[37]
$\text{M}/\text{CeO}_2$ , M=Pt, Pd, Ag and Au	ODH	1–2 nm	Catalyst	[38,39]
$\text{Ce}_{1-x}\text{Pt}_x\text{O}_2$	CH	4–6 nm	$\text{H}_2\text{-O}_2$ combination catalyst	[39,40]
$\text{Ce}_{1-x}\text{Pr}_x\text{O}_2$	CH	3–40 nm	Red pigment	[41]
$\text{Ni-YSZ}$ , (Ni,Co/Fe/Cu)- YSZ,	U	~40 nm	SOFC anode materials	[42,43]
$\text{Ln}(\text{Sr})\text{MO}_3$ , M=Fe, Mn and Co	CH/ODH	20–30 nm	SOFC cathode material	[44–48]
$\text{LaCrO}_3$	U	20 nm	Interconnect for SOFC	[49]
$\text{Y}_2\text{O}_3\text{-ZrO}_2/\text{YSZ}$	CH	59–65 nm	SOFC electrolyte	[50]
$\text{LiCo}_{0.5}\text{M}_{0.5}\text{O}_2$ (M=Ni, Mg, Mn and Zn)	U	5–10 $\mu\text{m}$	Cathode material for lithium batteries	[51]
$\text{MFe}_2\text{O}_4/\text{BaFe}_{12}\text{O}_{19}$	ODH	60–100 nm	Magnetic oxides	[52]
$\text{BaTiO}_3$	GLY/CA	18–25 nm	Dielectric material	[53]
$\text{Pb}(\text{Zr,Ti})\text{O}_3$	CA	~60 nm	Piezoelectric material	[54]
$\text{ZrO}_2$	GLY	23 nm	Oxygen sensor	[50]
$\text{ZnO}$	U	<100 nm	Varistor	[55]
$\text{ZrW}_2\text{O}_8$	U	38 nm	Negative thermal expansion	[56]
$\text{Eu}^{3+}/\text{Y}_2\text{O}_3$	GLY	20–30 nm	Red phosphor	[57]
	CA	25 nm	Red phosphor	[58]
$\text{LiMn}_2\text{O}_4$	PAA	30–60 nm	Lithium battery	[59]
$\text{In}_x\text{Ga}_{1-x}\text{O}_3$	HY	54–160 nm	Optical coating for sensors	[60]

U, urea; CH, carbonylhydrazide; ODH, oxalylidihydrazide; GLY, glycine; CA, citric acid; PAA, poly acrylic acid; HY, hydrazine; MA, metal acetate.

reduction of  $\text{NO}_x$  compared to the conventionally prepared ones [33,34]. Further, it is possible to selectively reduce  $\text{M}^{n+}/\text{Al}_2\text{O}_3$  composites by hydrogen to obtain M or alloy dispersed alumina [35].

Similarly, a variety of ceria and ceria-based oxide materials have been prepared by the SC method using ODH fuel. Some important oxides prepared are:  $\text{CeO}_2\text{-ZrO}_2$  (oxygen storage capacitor) [36,37],  $\text{M}^{n+}/\text{CeO}_2$ ; M = Pt, Pd, Ag, and Au [38] and  $\text{Ce}_{1-x}\text{Pt}_x\text{O}_2$  [39]. Ceria is a well-known catalyst support and Pt/ $\text{CeO}_2$  is used in catalytic converters (three-way catalyst TWC) in controlling pollution from car exhausts. Catalytic properties of  $\text{M}^{n+}/\text{CeO}_2$  were found to be several orders of magnitude better than those reported for the conventionally prepared catalysts. Ionically substituted Pt in  $\text{CeO}_2$  ( $\text{Ce}_{1-x}\text{Pt}_x\text{O}_2$ ) is found to be a particularly good catalyst for  $\text{H}_2\text{-O}_2$  recombination forming water at room temperature and is being developed as catalyst for valve regulated lead acid (VRLA) batteries with a long life of 15–20 years [40]. Praseodymium doped ceria ( $\text{Ce}_{1-x}\text{Pr}_x\text{O}_2$ ) prepared by SC is a red ceramic pigment in demand for replacing toxic Cd-sulpho selenide red pigment [41].

Another important application of SC is in the preparation of solid oxide fuel cell (SOFC) materials e.g. M/YSZ (M = Ni, Co) (anode) [42,43],  $\text{LnMO}_3$  (cathode) [44–48],  $\text{LaCrO}_3$  (interconnect) [49] and YSZ (electrolyte) [50]. Table 1 also lists other useful oxide materials prepared by SC such as: cathode material for lithium batteries ( $\text{LiCo}_{0.5}\text{M}_{0.5}\text{O}_2$ , M = Ni, Mg, Mn and Zn), ferrites (magnetic), dielectric and piezoelectric materials ( $\text{BaTiO}_3$ ,  $\text{Pb}(\text{Zr,Ti})\text{O}_3$ ) [51–54], ZnO (varistor) [55] and  $\text{ZrW}_2\text{O}_8$  (negative thermal expansion material) [56], yttria-based red phosphor [57,58],  $\text{LiMn}_2\text{O}_4$  [59] and  $\text{In}_x\text{Ga}_{1-x}\text{O}_3$  [60].

Recent research on SC has been directed towards a better understanding of the role of the fuel in controlling the particle size and microstructure of the combustion products. Interestingly, combustion of metal nitrate–glycine–ammonium nitrate redox mixtures [50] or metal acetate–aluminium nitrate urea mixtures exhibited non-flaming linear combustion to yield nanosize oxide products [27]. Voluminous zirconia, t- $\text{ZrO}_2$  formed by the combustion of aqueous solution containing a  $\text{ZrO}(\text{NO}_3)_2$ –glycine redox mixture is shown in Fig. 1. Formation of nanosize (~20 nm) t- $\text{ZrO}_2$  having large surface area ( $17 \text{ m}^2/\text{g}$ ) has been confirmed by TEM and surface area measurement. Other oxides were prepared using glycine fuel are  $\text{CeO}_2\text{-ZrO}_2$  and YSZ [50].

In brief, recent investigations on SC have led to the preparation of nanosize materials:

- By using the precursors like metal acetates and glycine, one can control combustion and prepare nanosize oxides.
- Carcinogenic hydrazine-based hydrazide fuels can be avoided.
- Combustion can be initiated by microwave, which yields uniform, narrow size distribution products.

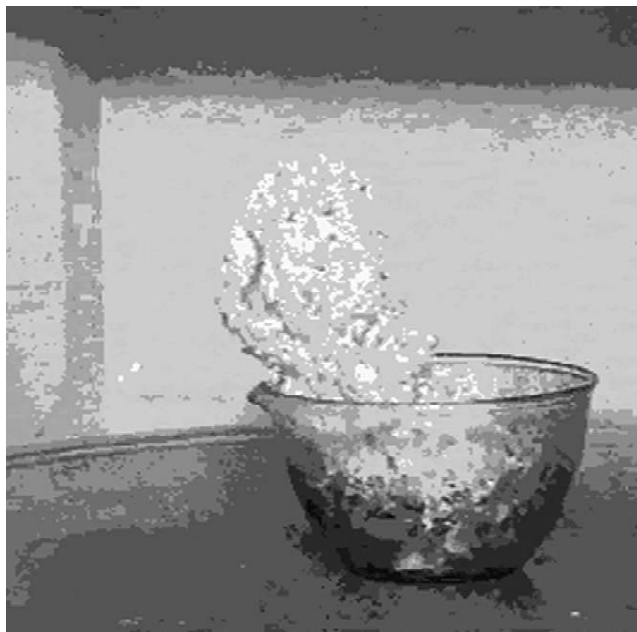


Fig. 1. t- $\text{ZrO}_2$  as formed by the combustion of  $\text{ZrO}(\text{NO}_3)_2$ +Glycine redox mixture.

#### 4. Conclusions

Combustion synthesis appears to meet the demands of Material Science Engineering in tailor making materials with desired composition, structure and property. Surprisingly, by controlling the processing parameters such as microwave initiation, gravity, precursors and additives to redox mixtures, it has been possible to obtain nanosize oxide, carbide and nitride materials and M/oxide composite catalysts using both SSC and SC. The usual processes practiced for the synthesis of nanomaterials are either by the breaking-down (physicist approach) or building-up (chemists approach) methods. Most of these procedures are too involved, need special equipment and expensive raw materials. The combustion method of preparing nanocrystalline materials although it appears to be a breaking down (destructive) process, is in fact, a building-up process as the product nuclei are formed initially and grow.

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#### References

Papers of particular interest, published within the annual period of review, have been highlighted as:

\* of special interest;

\*\* of outstanding interest.

- [1] Patil KC, Aruna ST, Ekambaram S. Combustion synthesis. *Curr Opin Solid State Mater Sci* 1997;2:158–65.
- [\*2] Patil KC, Aruna ST. In: Borisov AA, De Luca LT, Merzhanov AG, Scheck YN, editors. Redox methods in SHS practice in self-propagating high temperature synthesis of materials. New York: Taylor & Francis; 2002. Collection of 17 articles by experts in the area reflecting the trends in SHS covering theory and practice of combustion, material synthesis and applications.
- [\*\*3] Merzhanov AG. SHS research and development handbook. Chernogolovka, Russia: Russian Academy of Sciences; 1999. Contains valuable and up-to-date information on the state of the art of SHS products, manufacture, equipment, instrumentation and application. The information is of great interest to both academics and technologists.
- [\*4] Varma A. Form from fire. *Sci Am* 2001;283:44–7, Meant for nonspecialist. Useful to materials scientists and technologists.
- [\*\*5] Varma A, Rogachev AS, Mukasyan AS, Hwang S. Combustion synthesis of advanced materials: principles and applications. *Adv Chem Eng* 1998;24:79–226, This article summarizes the current status of combustion synthesis of advanced ceramics, intermetallics and composites. The topics covered include types of combustion: SHS and volume combustion; laboratory technique and production technology, theory, modeling and possible mechanisms of combustion reactions. Various experimental techniques used such as time resolved X-ray diffraction, high speed microscopic video recording, reaction wave quenching and electrothermography are described.
- [6] Maglia F, Anselmi-Tamurini U, Bertolino N, Milanese C, Munir ZA. Synthesis of Cr–Si intermetallic compounds by field-activated combustion synthesis. *J Mater Res* 2000;15:1098–109.
- [7] Gedevisanishvili S, Munir ZA. The synthesis of TiB<sub>2</sub>–TiAl<sub>3</sub> composites by field-activated combustion. *Mater Sci Eng A* 1998;246:81–5.
- [8] Anselmi-Tamurini U, Maglia F, Spinolo G, Munir ZA. Nickel/yttria-stabilised zirconia cermets from combustion synthesis: effect of process parameters on product microstructure. *J Am Ceram Soc* 1998;81:1765–72.
- [9] Shon IJ, Munir ZA. Synthesis of TiC and TiC–Cu functionally graded materials by electrothermal combustion. *J Am Ceram Soc* 1998;81:3242–8.
- [10] Roberto T, Munir ZA. Effect of particle size on the reaction wave propagation in the combustion synthesis of Al<sub>2</sub>O<sub>3</sub>–ZrO<sub>2</sub>–Nb composites. *J Am Ceram Soc* 1999;82:1985–2077.
- [11] Carrillo-Heian EM, Graeve OA, Feng A, Faghih JA, Munir ZA. Modeling studies of the effect of thermal and electrical conductivities and relative density of field-activated self-propagating combustion synthesis. *J Mater Res* 1999;14:1949–58.
- [12] Aguas MD, Affleck L, Parkin IP, Kuznetsov MV, Steer A, Pankhurst QA, Barquin LF, Roberts MA, Boamfa ML, Jos A, Perenboom AJ. The effect of large magnetic fields on solid state combustion reactions: novel microstructure, lattice contraction and reduced coercivity in barium hexaferrite. *J Mater Chem* 2000;10:235–7.
- [13] Affleck L, Aguas MD, Pankhurst QA, Parkin IP, Steer WA. Combustion synthesis of BaFe<sub>12</sub>O<sub>19</sub> in an external magnetic field: time-resolved X-ray diffraction (TRXRD) studies. *Adv Mater* 2000;18:1359–62.
- [14] Lau C, Mukasyan A, Pelekh A, Varma A. Mechanistic studies in combustion synthesis of NiAl–TiB<sub>2</sub> composites: effects of gravity. *J Mater Res* 2001;16:1614–25.
- [15] Xanthopoulos G. Oxide catalysts for pyrolysis of diesel fuel made by self propagating high temperature synthesis (SHS) Part II: Fe–Cr oxide catalysts based on chromite concentrates. *Appl Catal* 1999;187:79–88.
- [16] Ming Q, Nersesyan MD, Wagner A, Ritchie J, Richardson JT, Luss D, Jacobson AJ, Yang YL. Combustion synthesis and characterization of Sr and Ga doped LaFeO<sub>3</sub>. *Solid State Ionics* 1999;122:113–21.
- [17] Wagner AL, Jacobson AJ, Richardson JT, Luss D. Reaction characteristics of La<sub>0.84</sub>Sr<sub>0.16</sub>CrO<sub>3</sub>. *J Mater Sci* 1999;34:3035–41.
- [18] Ming Q, Hung J, Yang YL, Nersesyan MD, Jacobson AJ, Richardson JT, Luss D. Combustion synthesis of La<sub>0.2</sub>Sr<sub>0.8</sub>Cr<sub>0.2</sub>Fe<sub>0.8</sub>O<sub>3-x</sub>. *Combust Sci Technol* 1998;138:279–85.
- [19] Ming Q, Nersesyan MD, Lin S, Richardson JT, Luss D, Shiryayev AA. A new route to synthesize La<sub>1-x</sub>Sr<sub>x</sub>MnO<sub>3</sub>. *J Mater Sci* 2000;35:3599–606.
- [20] Li L, Akiyama T, Yagi J. Activity and capacity of hydrogen storage alloy Mg<sub>2</sub>NiH<sub>4</sub> produced by hydriding combustion synthesis. *J Alloys Comp* 2000;308:98–103.
- [21] Yong-hua L, Rong L, Yi-yi L. Pore characteristics of porous NiTi alloy fabricated by combustion synthesis. *J Alloys Comp* 2001;319:108–18.
- [22] Chun-Nan L, Shyan-Lung C. Combustion synthesis of aluminum nitride powder using additives. *J Mater Res* 2001;16:2200–8.
- [23] Vaidhyanathan B, Agarwal DK, Roy R. Novel synthesis of nitride powders by microwave-assisted combustion. *J Mater Res* 2000;15:974–81.
- [\*24] Mimani T. Fire synthesis: preparation of alumina related products. *Resonance* 2000;5:50–7, Simple and educational. Useful article for beginners in the field of solution combustion synthesis.
- [25] Kiminami RHGA, Morelli MR, Folz DC, Clark DE. Microwave synthesis of alumina powders. *Am Ceram Soc Bull* 2000;79:63–7.
- [26] Bhaduri S, Bhaduri SB, Zhou E. Auto ignition synthesis and consolidation of Al<sub>2</sub>O<sub>3</sub>–ZrO<sub>2</sub> nano/nano composite powders. *J Mater Res* 1998;13:156–65.
- [27] Mimani T. Instant synthesis of nanoscale spinel aluminates. *J Alloys Comp* 2001;315:123–8.
- [28] Bhaduri S, Bhaduri SB, Prisbery KA. Auto ignition synthesis of nanocrystalline MgAl<sub>2</sub>O<sub>4</sub> and related nanocomposites. *J Mater Res* 1999;14:3571–80.
- [29] Quenard O, Grave De E, Laurent C, Rousset A. Synthesis, characterization and thermal behaviour of Fe<sub>0.65</sub>Co<sub>0.35</sub>MgAl<sub>2</sub>O<sub>4</sub> and Fe<sub>0.65</sub>Ni<sub>0.35</sub>MgAl<sub>2</sub>O<sub>4</sub> nanocomposite powders. *J Mater Chem* 1997;7:2457–67.
- [30] Mimani T, Ghosh S. Combustion synthesis of cobalt pigments: blue and pink. *Curr Sci* 2000;78:892–6.
- [31] Shikao S, Wang J. Combustion synthesis of Eu<sup>3+</sup> activated Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> phosphor nanoparticles. *J Alloys Comp* 2001;327:82–6.
- [32] Ravichandran D, Roy R, Ravindranathan P, White WB. Combustion synthesis of hexaluminate phosphors. *J Am Ceram Soc* 1999;82:1082–166.
- [33] Bera P, Patil KC, Jayaram V, Hegde MS, Subbana GN. Combustion synthesis of nano metal particles supported on α-Al<sub>2</sub>O<sub>3</sub>: CO oxidation and NO reduction catalysts. *J Mater Chem* 1999;9:1801–5.
- [34] Bera P, Patil KC, Hegde MS. Oxidation of CH<sub>4</sub> and C<sub>3</sub>H<sub>8</sub> over combustion synthesized nanosize metal particles supported on α-Al<sub>2</sub>O<sub>3</sub>. *Phys Chem Chem Phys* 2000;2:373–8.
- [35] Greca MC, Moraes C, Segadaes AM. Palladium/alumina catalysts: effect of the processing route on catalytic performance. *Appl Catal A* 2001;26:267–76.
- [36] Aruna ST, Patil KC. Combustion synthesis and properties of nanostructured ceria–zirconia solid solutions. *Nanostruct Mater* 1998;10:955–64.
- [37] Lamas DG, Juarez RE, Lascalea GE, Walsoe de Reca NE. Synthesis of compositionally homogeneous, nanocrystalline ZrO<sub>2</sub>–35 mol% CeO<sub>2</sub> powders by gel combustion. *J Mater Sci Lett* 2001;20:1447–9.
- [38] Bera P, Patil KC, Jayaram V, Subbana GN, Hegde MS. Ionic dispersion of Pt and Pd on CeO<sub>2</sub> by combustion method: effect of metal–ceria interaction on catalytic activities for NO reduction, CO and hydrocarbon oxidation. *J Catal* 2000;196:293–301.
- [39] Bera P, Hegde MS, Patil KC. Combustion synthesised Ce<sub>1-x</sub>Pt<sub>x</sub>O<sub>8</sub> (x=0.005, 0.01 and 0.02, δ=0.07 and 0.1): a novel room temperature H<sub>2</sub>–O<sub>2</sub> recombination catalyst. *Curr Sci* 2001;80:1576–8.
- [40] Hariprakash B, Bera P, Martha SK, Gaffoor SA, Hegde MS, Shukla

- AK. Ceria supported platinum as hydrogen–oxygen recombination catalyst for sealed lead-acid batteries. *Electrochem Solid-State Lett* 2001;4:A23–6.
- [41] Aruna ST, Ghosh S, Patil KC. Combustion synthesis and properties of  $Ce_{1-x}Pr_xO_{2-\delta}$  red ceramic pigments. *Int J Inorg Mater* 2001;3:387–92.
- [42] Aruna ST, Muthuraman M, Patil KC. Synthesis and properties of Ni-YSZ cermet: anode material for solid oxide fuel cells. *Solid State Ionics* 1998;111:45–51.
- [43] Ringuede A, Labrincha JA, Frade JR. A combustion synthesis method to obtain alternative cermet materials for SOFC anodes. *Solid State Ionics* 2001;141–142:649–56.
- [44] Aruna ST, Muthuraman M, Patil KC. Combustion synthesis and properties of strontium substituted lanthanum manganites,  $La_{1-x}Sr_xMnO_3$  ( $0 \leq x \leq 0.3$ ). *J Mater Chem* 1997;7:2499–503.
- [45] Xie P, Zhang W, Yan K, Jing L, Zhang W, Xia S. Size-controllable gly-nitrate low temperature combustion synthesis (LCS) of nanocrystalline  $La_xSr_{1-x}MnO_3$ . *J Alloys Comp* 2000;311:90–2.
- [46] Aruna ST, Muthuraman M, Patil KC. Studies on combustion synthesised  $LaMnO_3$ – $LaCoO_3$  solid solutions. *Mater Res Bull* 2000;35:289–96.
- [47] Aruna ST, Muthuraman M, Patil KC. Studies on strontium substituted rare earth manganites. *Solid State Ionics* 1999;120:275–80.
- [48] Suresh K, Panchapagesan TS, Patil KC. Synthesis and properties of  $La_{1-x}Sr_xFeO_3$ . *Solid State Ionics* 1999;126:299–305.
- [49] Park HK, Han YS, Kim DK, Kim CH. Synthesis of  $LaCrO_3$  powders by microwave induced combustion of metal nitrate–urea mixture solution. *J Mater Sci Lett* 1998;17:785–7.
- [50] Mimani T, Patil KC. Solution combustion synthesis of nanoscale oxides and their composites. *Mater Phys Mech* 2001;4:1–5.
- [51] Julien C, Camacho-Lopez MA, Mohan T, Chitra S, Kalayani P, Gopakumar S. Combustion synthesis and characterization of substituted lithium cobalt oxides in lithium batteries. *Solid State Ionics* 2001;141–142:549–57.
- [52] Patil KC, Mimani T. Preparation and properties of nanocrystalline magnetic oxides. *Mag Soc India Bull* 2000;22:21–6.
- [53] Anuradha TV, Ranganathan S, Mimani T, Patil KC. Combustion synthesis of nanostructured barium titanate. *Scripta Mater* 2001;44:2237–41.
- [54] Schafer J, Sigmund W, Roy S, Aldinger F. Low temperature synthesis of ultrafine  $Pb(Zr,Ti)O_3$  powder by sol gel combustion. *J Mater Res* 1997;12:2518–21.
- [55] Sousa VC, Segadaes AM, Moreli MR, Kiminami RHGA. Combustion synthesized powders for varistor ceramics. *Int J Inorg Mater* 1999;1:235–41.
- [56] Kameswari U, Sleight AW, Evans JSO. Rapid synthesis of  $ZrW_2O_8$  and related phases, and structure refinement of  $ZrW_2MoO_8$ . *Int J Inorg Mater* 2000;2:333–7.
- [57] Fagherazzi G, Polizzi S, Bettinelli M, Speghini A. Yttria based nanosized powders: a new class of fractal materials obtained by combustion synthesis. *J Mater Res* 2000;15:586–9.
- [58] Roy S, Sigmund W, Aldinger F. Nanostructured yttria powders via gel combustion. *J Mater Res* 1999;14:1524–31.
- [59] Hyu-Bum P, Kim J, Chi-Woo L. Synthesis of  $LiMn_2O_4$  powder by auto-ignited combustion of poly(acrylic acid)-metal nitrate precursor. *J Power Sources* 2001;92:124–30.
- [60] Garcia R, Hirata GA, McKittrick J. New combustion synthesis technique for the production of  $(In_xGa_{1-x})_2O_3$  powders: Hydrazine/metal nitrate method. *J Mater Res* 2001;16:1059–65.