Novel palladium substituted cerium-tin-oxides as highly active catalysts for continuous Suzuki-Miyaura reactions

G. J. Lichtenegger,[1] P.A. Deshpande,[2] H. Gruber-Woelfler,[1] J. G. Khinast[1]
[1] Graz University of Technology, Institute of Process and Particle Engineering, Graz, Austria
[2] Indian Institute of Technology, Department of Chemical Engineering, Kharagpur, India

Introduction

In the last decades great effort has been made to develop heterogeneous catalysts for Suzuki-Miyaura cross-coupling reactions. A wide variety of immobilized organic ligands and their palladium-complexes as well as ligand-free systems on different solid supports (e.g. activated carbon [1], organic polymers [2], or silica [3]) has been reported. A special issue in this context is the leaching [4] of the metal as well as the stability of the catalysts in continuous flow systems.
In this contribution we present palladium substituted mixed cerium-tin-oxides (general formula $Ce_{0.99-x}Sn_xPd_{0.01}O_{2-\delta}$) as heterogeneous catalysts for continuous Suzuki-Miyaura cross coupling reactions. The Pd-substituted Ce-Sn-oxides with different proportions of tin (x = 0, 0.2, 0.495, 0.79, 0.99) have been prepared using solution combustion methods [5].
With that method several grams of catalyst can be prepared in less than 3 hours out of inexpensive and environmentally friendly precursors (ceric ammonium nitrate, tin(II) oxalate, palladium(II) chloride, glycine).
The obtained catalysts show an activity of 2000 h^{-1} in aqueous media at moderate temperatures and can be reused in batch experiments several times without significant loss of activity. Furthermore, the catalyst proved to be highly stable for Suzuki-Miyaura reactions carried out in a packed bed microreactor system.
All in all, the novel palladium substituted cerium-tin-oxides proved to be easily preparable, inexpensive and highly active catalysts suitable for continuous Suzuki-Miyaura cross-coupling reactions.

Synthesis

Five Catalysts with different proportions of tin were synthesized from ceric ammonium nitrate, tin(II) oxalate, palladium (II) chloride and glycine using the solution combustion method.

Catalyst 1	$Ce_{0.99}Pd_{0.01}O_{2-\delta}$
Catalyst 2	$Ce_{0.79}Sn_{0.2}Pd_{0.01}O_{2-\delta}$
Catalyst 3	$Ce_{0.495}Sn_{0.495}Pd_{0.01}O_{2-\delta}$
Catalyst 4	$Ce_{0.2}Sn_{0.79}Pd_{0.01}O_{2-\delta}$
Catalyst 5	$Sn_{0.99}Pd_{0.01}O_{2-\delta}$

The catalyst precursors were dispersed in water and a minimum of nitric acid was added until a clear solution was obtained. The precursor solution was introduced in a muffle furnace where the combustion reaction took place. After grinding and heating for another 5 hours, the resulting porous solid could be used directly as catalyst

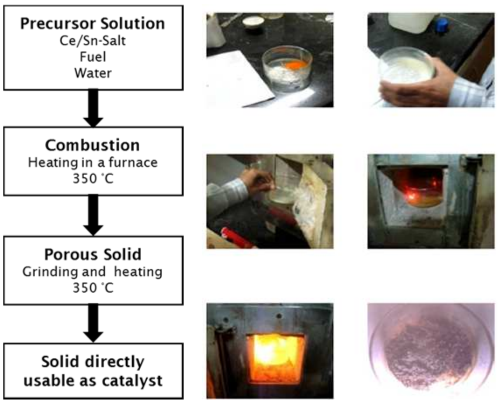

Fig. 1: Solution combustion synthesis

XRD analysis of the catalysts revealed a cubic crystal system for catalyst 1, 2 and 3, a mixed tetragonal/cubic system for catalyst 4 and a tetragonal system for catalyst 5. Diffraction peaks corresponding to Pd metal or PdO could not be observed.

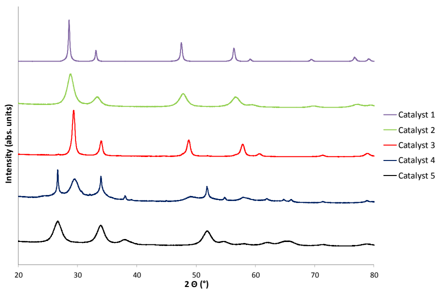

Fig. 2: XRD-spectra

Batch

The activity of the catalysts was tested for the Suzuki-Miyaura cross-coupling reaction of 4-bromotoluene and phenylboronic acid using potassium carbonate as base in an aqueous ethanol solution (EtOH:H_2O = 7:3 v/v) at 70 °C.

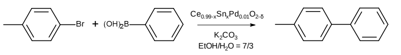

Fig. 3: Suzuki-Miyaura cross-coupling reaction

Catalyst 3 ($Ce_{0.495}Sn_{0.495}Pd_{0.01}O_{2-\delta}$) proved to be the most active catalyst under this conditions. Thus, this catalyst was used for continuous flow experiments.

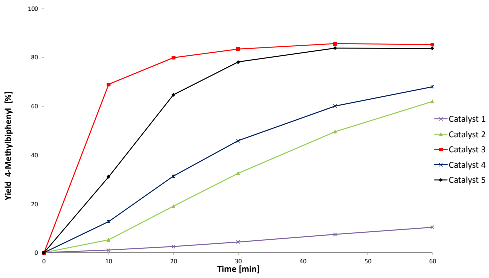

Fig. 4: Batch-experiments

Table 1: Results – Batch experiments

Cat.	Molecular Formula	Yield[a;b] [%]	TOF [h^{-1}]
1	$Ce_{0.99}Pd_{0.01}O_{2-\delta}$	10; 39	251
2	$Ce_{0.79}Sn_{0.20}Pd_{0.01}O_{2-\delta}$	62; 85	1789
3	$Ce_{0.495}Sn_{0.495}Pd_{0.01}O_{2-\delta}$	85; 89	1803
4	$Sn_{0.79}Ce_{0.20}Pd_{0.01}O_{2-\delta}$	68; 85	1787
5	$Sn_{0.99}Pd_{0.01}O_{2-\delta}$	84; 90	1912
blind	SnO_2	0; 0	0
blind	CeO_2	0; 0	0

Yields were determined with GC analysis using dodecane as internal standard after [a] 1h and [b] after 3h. Blind samples (pure ceria and SnO_2) showed no activity.

Continuous Flow

Continuous flow-experiments were performed in the so called Plug&Play-Reactor engineered and constructed by OneA engineering (Vöcklabruck, Austria). This microreactor features a modular design. Reaction, pumping, heating and mixing devices are designed as displaceable modules. This modular approach provides the possibility to optimize the process performance over a wide range of reaction conditions and allows the implementation of process analytical tools. The reaction module is designed as catalytic fixed bed flow reactor. The use of displaceable standard HPLC-columns as reaction modules provides flexibility regarding the amount and volume of used catalyst for different reactions and flow-rates.
Figure 6 shows the performance of catalyst 3 in a continuous flow experiment. Under the chosen conditions, the relative yield of 4-phenyltoluene could be kept above 80 % for at least 16 h which corresponds to an absolute yield of 0.15 g/h and 3.72 g/d, respectively.
Figure 7 shows the catalytic performance of the same catalyst under changing reaction conditions (temperature and flow rate) .

a) b) c)

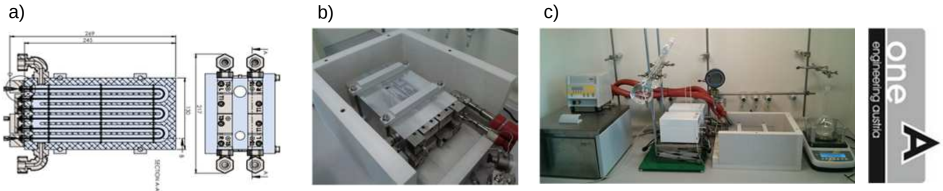

Figure 5: The Plug&Play-Reactor: a) schematic view, b) the reactor, c) the complete set-up

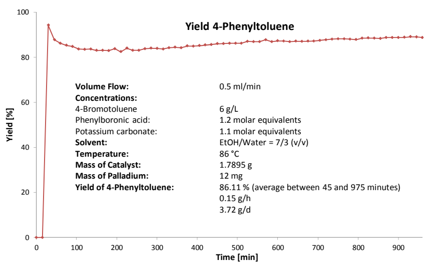

Fig. 6: Flow-experiments: test of stability

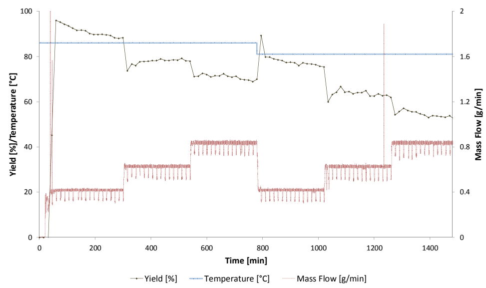

Fig. 7: Flow-experiments: change of temperature and flow-rate

Conclusions:

- **Solutions combustion is an easy and rapid method for the synthesis of palladium substituted cerium tin oxides at the gram scale**
- **The resulting oxides are highly active catalysts for Suzuki-Miyaura cross-coupling reactions**
- **The catalysts show good stability in continuous flow reactions and the continuous synthesis of biaryls at the gram scale could be achieved**

Contact

Dr. Heidrun Gruber-Woelfler
Graz University of Technology
Institute of Process and Particle Engineering
Inffeldgasse 13/III
8010 Graz, Austria
e-mail: woelfler@tugraz.at

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