The University of Nottingham

3rd International Slag Valorisation Symposium,
19-20 March 2013, **Leuven**, Belgium

武漢大學 Wuhan University

The FFC Cambridge Process: Principle, Practice and Prospect

with a Focus on Titania, Ilmenite and Ti-Rich Slag

Panzhihua, China

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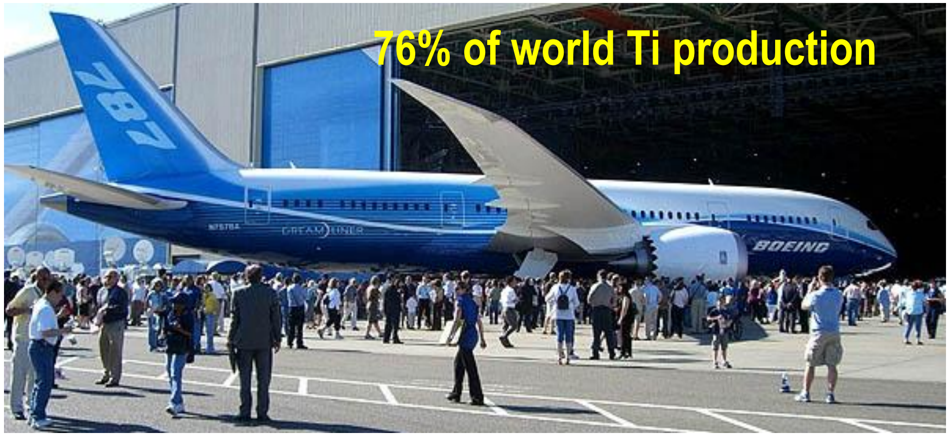
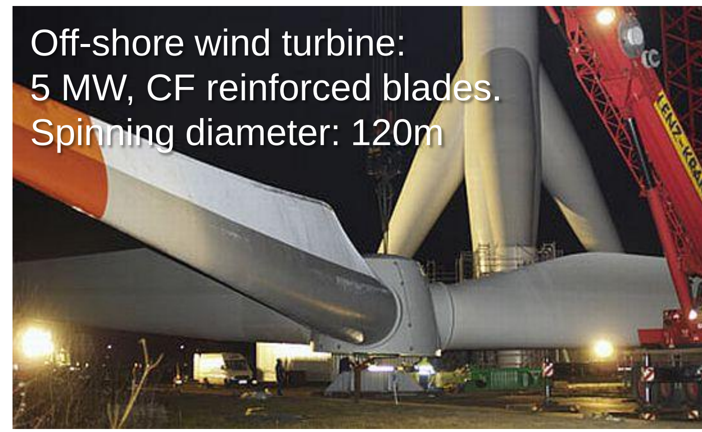
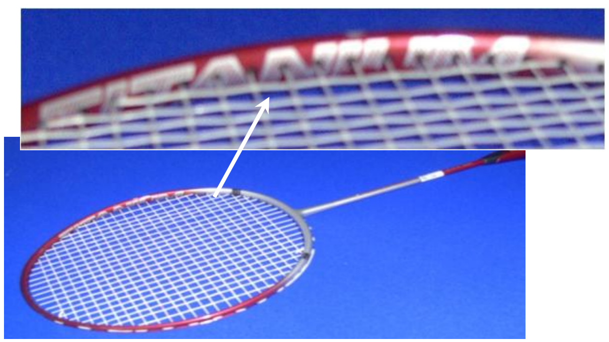
Titanium Economy







Titanium badminton racket

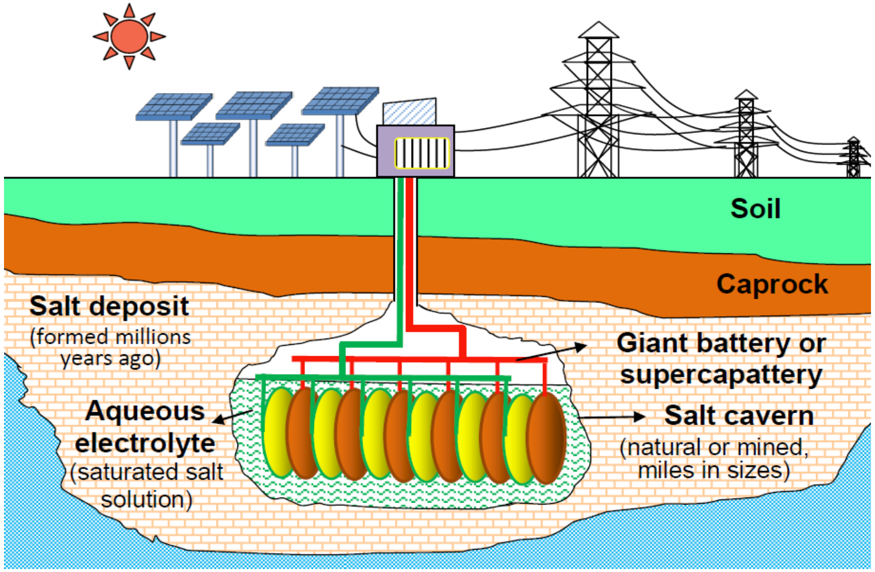
Citizen Eco-Drive titanium watch

Titanium ring

Titanium implants

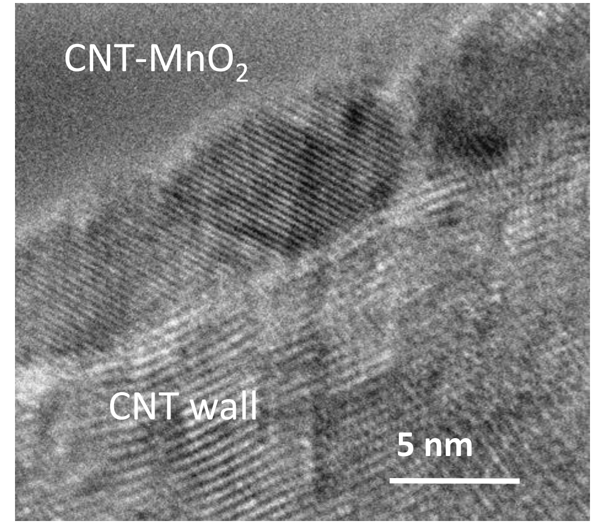
Titanium Supercapattery

Electricity in Salt Caverns (> MW)

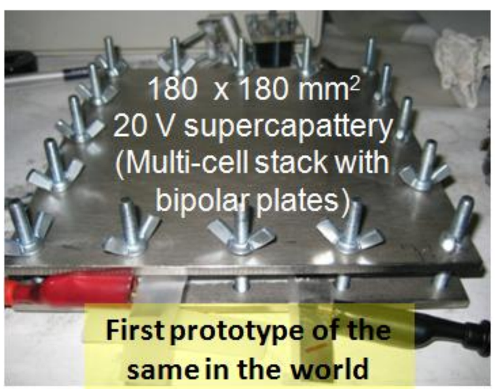


☹
Seawater is highly corrosive to many metals, including stainless steel.

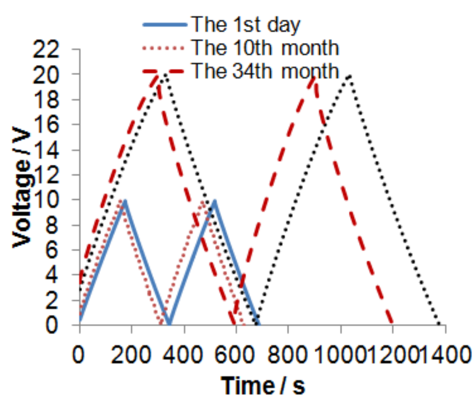
Aqueous electrolyte: high conductivity, high heat capacity, wide temperature range, low environmental impact, **and "Free" .**



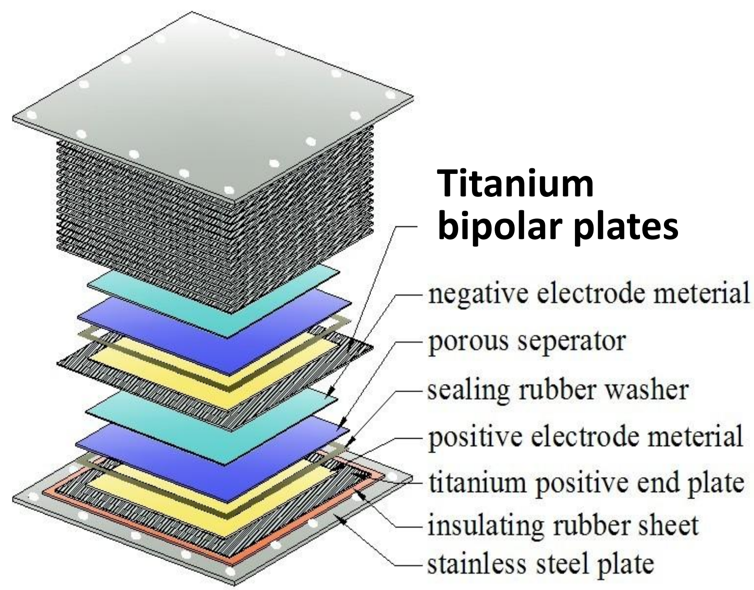
Crucial material: C-nanotubes coated with metal oxide or conducting polymer for use in aqueous chloride electrolytes.



Maximum stack power: > 300 W.



On-going test since 07/2009.



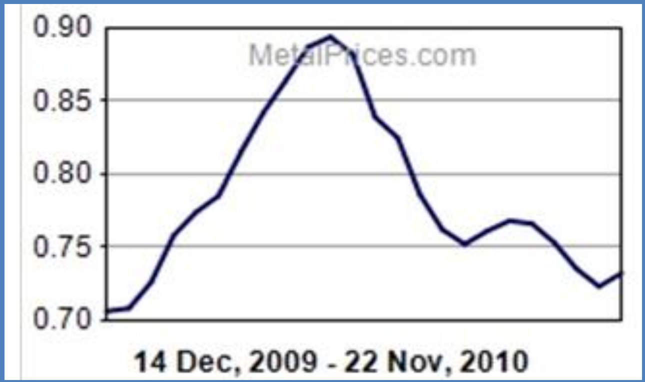
Titanium vs. Steel

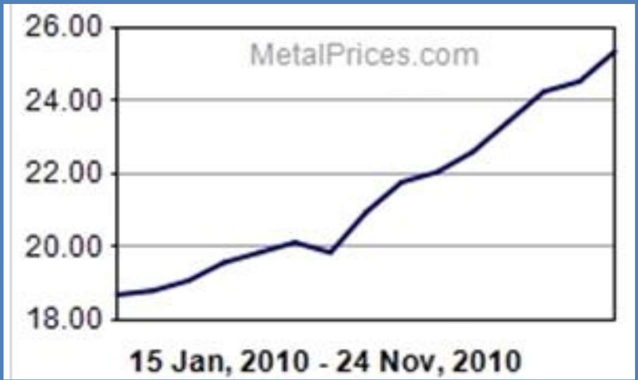
World Production (mt/yr)

	2008	2009
Raw steel	1,330	1,100
Titanium	0.16	0.11

Market Price ($/kg)

Cold rolled steel vs. **Ti-6Al-4V ingot**





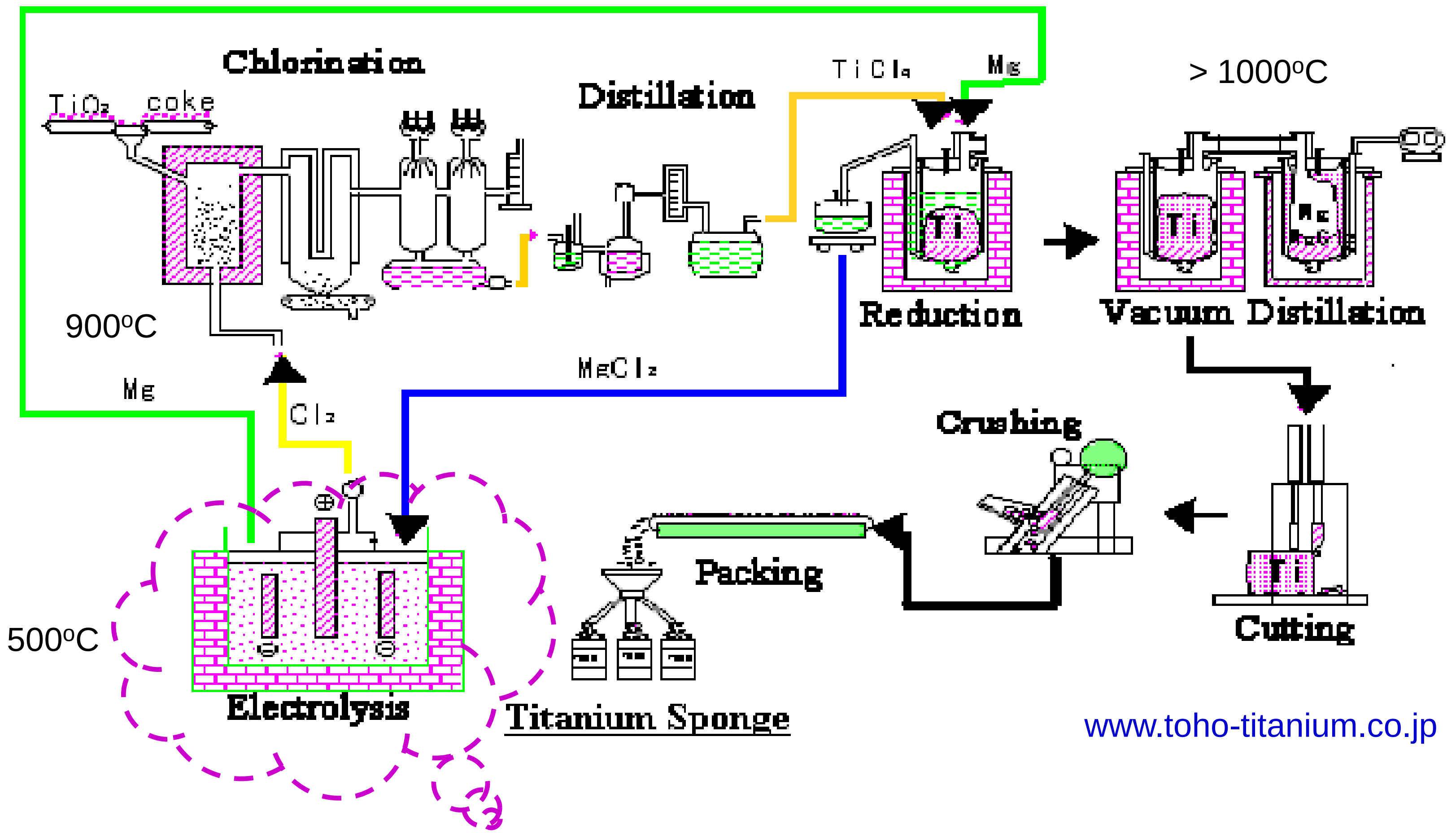
Energy consumption

Steel: 6~8 kWh/kg **Titanium:** ~55 kWh/kg

http://metalprices.com/ http://www.steelonthenet.com/price_info.html

Titanium extraction by the Kroll Process

$C + TiO_2 + 2Cl_2 = TiCl_4 + CO_2$ $\quad$ $Mg + TiCl_4 = Ti + 2MgCl_2$ $\quad$ $MgCl_2 \overset{\text{electrolysis}}{=} Mg + Cl_2$



Regeneration of Mg and Cl_2 by molten salt electrolysis makes the modern Kroll Process an **indirect but inefficient** electrolytic process.

Limitations of the Kroll Process

The Kroll Process

- operates in a batch reactor at a scale of a few tonnes (d. & h: ~1.5 & ~8 m),
- takes two weeks for each production cycle,
- uses expensive feed materials (Cl_2, Mg & C),
- **consumes ~55 kWh/kg-Ti ,**
- vs. *cheapest manmade material~: 6 kWh/kg-steel*
- and emits about equal amount of CO_2.

Energy content in C and Mg:

$C + O_2(g) = CO_2(g)$
$\Delta G^o_{(300\text{-}2000K)} = -9.2$ kWh/kg-C

$2Mg + O_2(g) = 2MgO$
$\Delta G^o_{(1000\ K)} = -11.3$ kWh/kg-Mg

As produced
Ti sponge

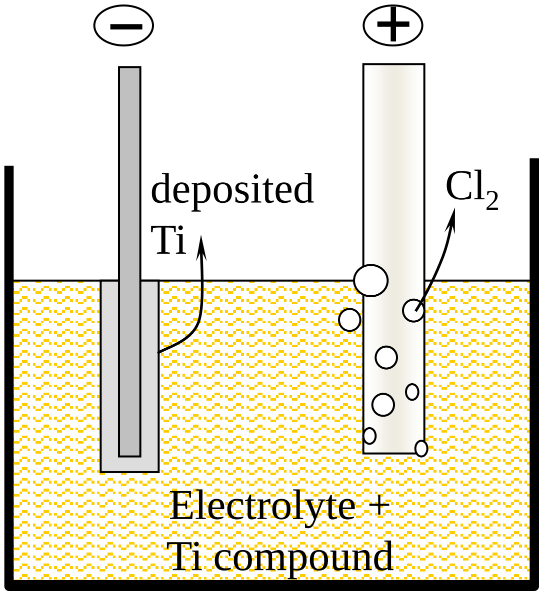
Ti ingot (*via* arc melting)

http://www.toho-titanium.co.jp/en/products/sponge.html

"It might, however, be fair to say, that titanium will be made competitively by **fusion electrolysis** within the next 5 to 10 years."
(W. Kroll, **1959**, Extractive Metallurgy Division Lecture, American Institute of Mining, Metallurgy, and Petroleum Engineers)

Electrolytic Extraction

Conventional concept of electrolysis



Dissolving titanium compounds (e.g. $TiCl_4$ and TiO) in molten salts

$TiCl_4 = Ti^{4+} + 4Cl^-$ or $TiO = Ti^{2+} + O^{2-}$

Electrowinning titanium from the molten salt solution (electro-deposition)

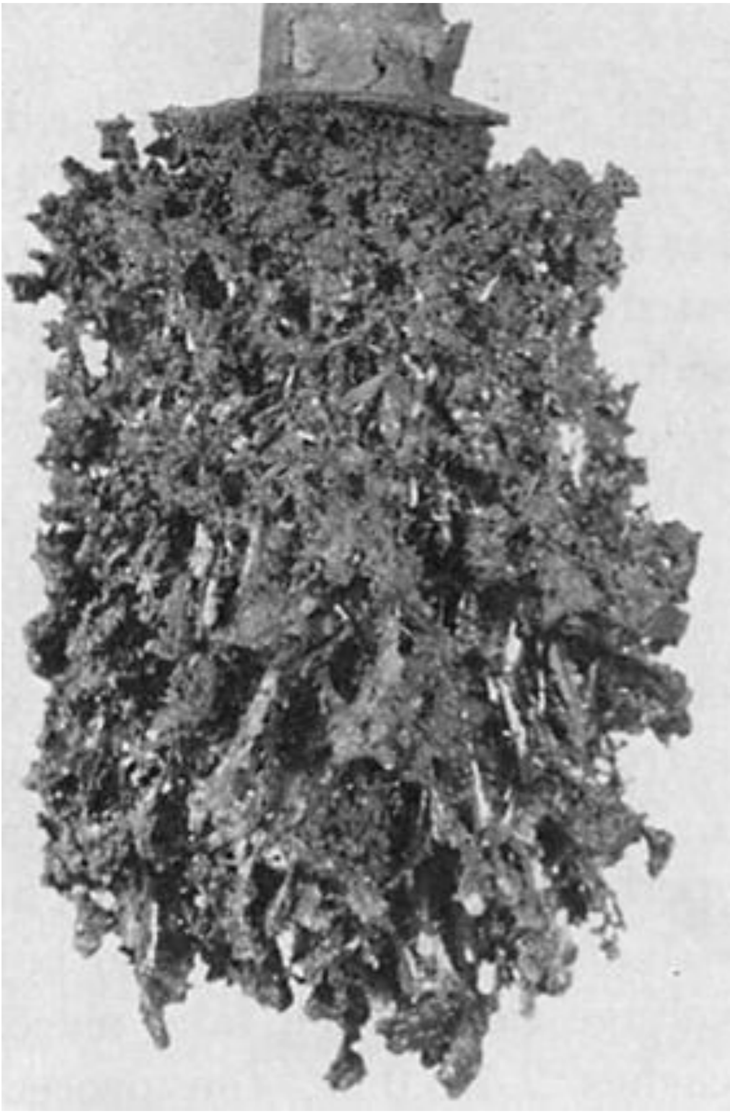
$Ti^{4+} + 4e = Ti$ or $Ti^{2+} + 2e = Ti$ (cathode)

energy = nFEW / mM = 6.72 kWh/kg-Ti

n: number of electrons transferred (4)
F: Faraday constant (96500 C/mol)
E: voltage of electrolysis (3.0 V)
W: mass of titanium produced (1 t = 10^6 g)
m: number of joules per kWh (3.6×10^6 J)
M: molar mass of titanium (47.88 g)

Kroll Process:
~55 kWh/kg-Ti

Advantage: Cost = £0.10 (UK) x 6718 = £671.8 / tonne Ti

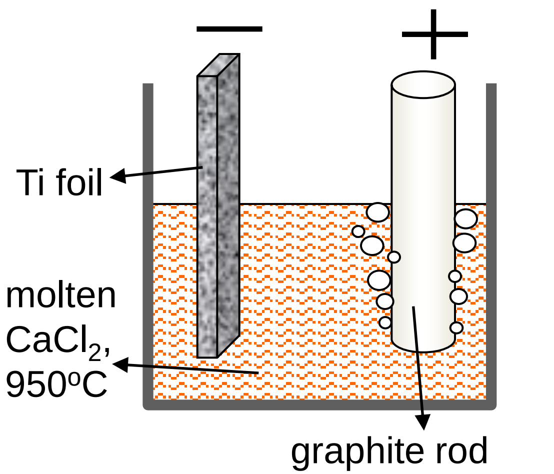


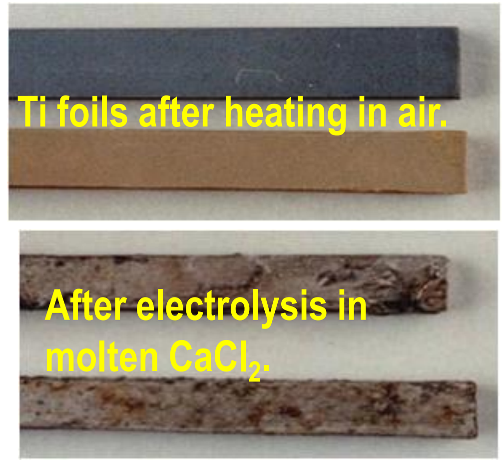
The dendritic deposit of titanium from K_2TiF_6 in 850-950^oC molten NaCl.

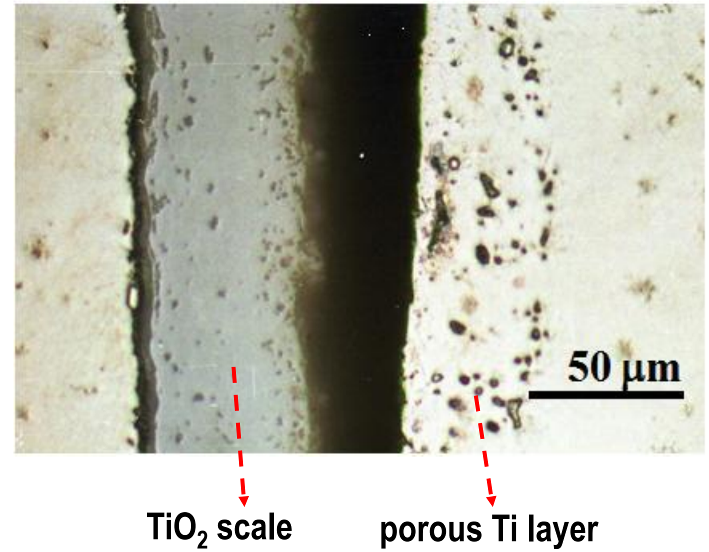
[M. A. Steinberg, M. E. Sibert, S.S. Carlton, & E. Wainer, *J. Electrochem. Soc.*, 102 (1955) 252.]

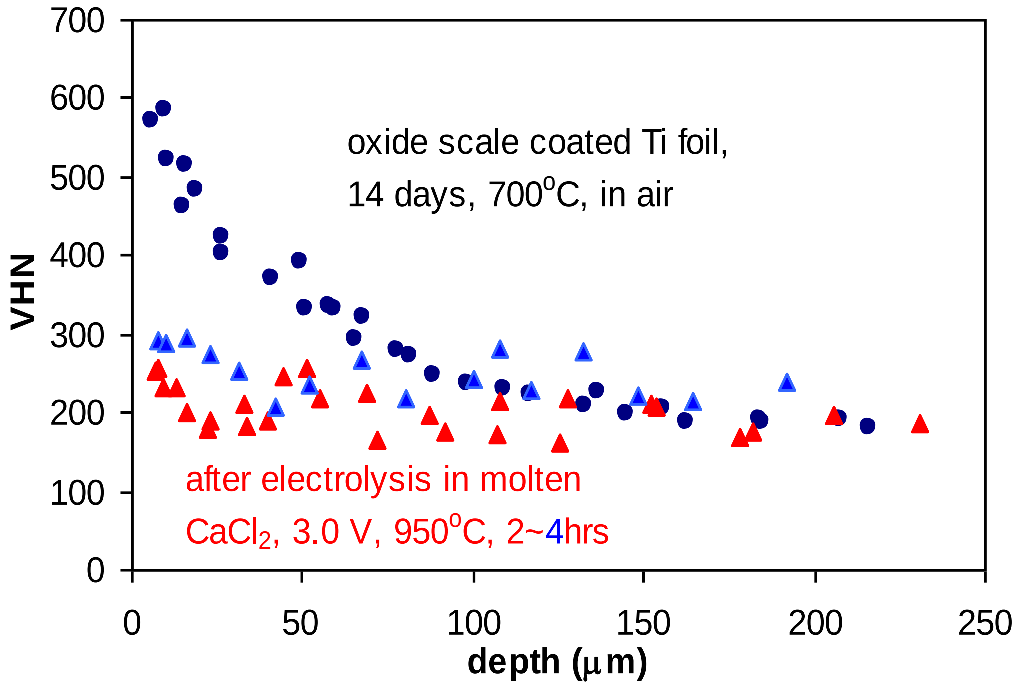
Production of titanium by **electro-deposition** from a solution has been researched for more than half a century, supported by billions of dollars around the world, **yet it still has not succeeded at the industrial scale**.

Reduction of Solid TiO_2 ---- The Discovery in Late 1996









Chen, Fray, Farthing, ***Metall. Mater. Trans. B,*** 32 (2001) 1041

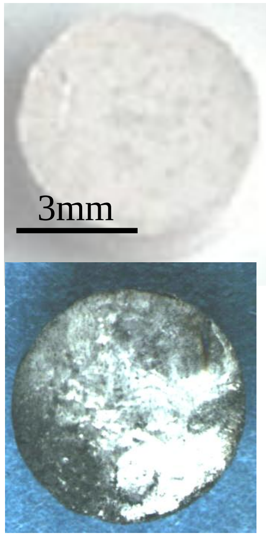
Question:

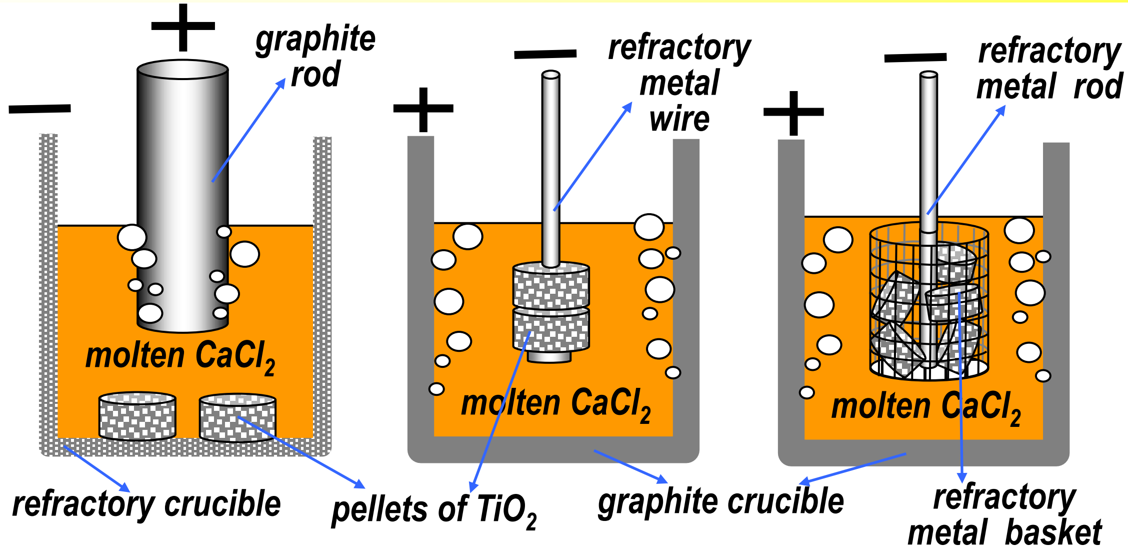
Are these observations an indication of electrochemical reduction of ***solid*** TiO_2 that is an ***insulator***?

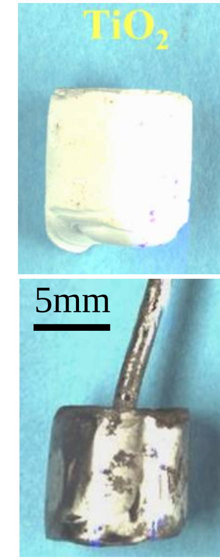
TiO_2 (solid) + 4e = Ti + $4O^{2-}$

Chen, Fray, Farthing, ***Nature***, 407 (2000) 2570.

Electro-Reduction of Solid Metal Oxides in Molten Salts ---The FFC Cambridge Process via Oxygen Ionisation







Cathode:

TiO_2 (solid) + 4e = Ti (solid) + $2O^{2-}$

Graphite or Inert Anode:

xO^{2-}+C = CO_x+ 2xe; or $2O^{2-}$ = O_2 (gas) + 4e,

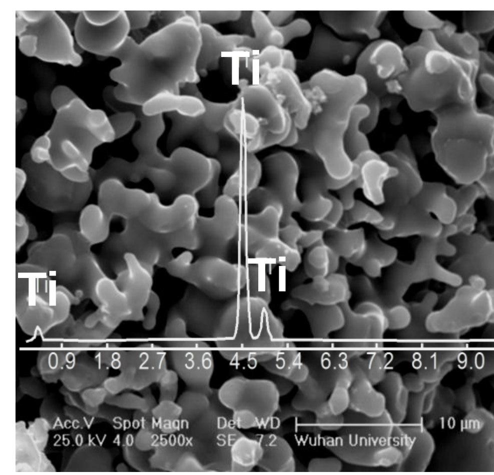
Overall cell reaction (inert anode) :

TiO_2 (solid) = Ti (solid) + O_2 (gas)

Inert Anode

SnO_2;
$CaRuO_3$-$CaTiO_3$;
Solid O^{2-} conductor;
Cermets

O^{2-} cond. electrolyte
$CaCl_2$, $BaCl_2$, LiCl…



(1) Chen, Fray, Farthing, ***Nature***, 407(2000)2570.
(2) Schwandt, Fray, ***Electrochim.. Acta***, 51 (2005) 66.
(3) Jiang, Hu, ..., Jin, Chen, ***Angew. Chem. Int. Edit.***, 45 (2006) 428.
(4) Li, Jin, Huang, Chen, ***Angew. Chem. Int. Edit.,*** 49 (2010) 3203.
(5) Jiao, Fray, ***Mater. Metall. Trans. B***, 41 (2010) 74.
(6) Zhao, Lu, Zhong, ... ***Electrochim. Acta*** 55 (2010) 2996.

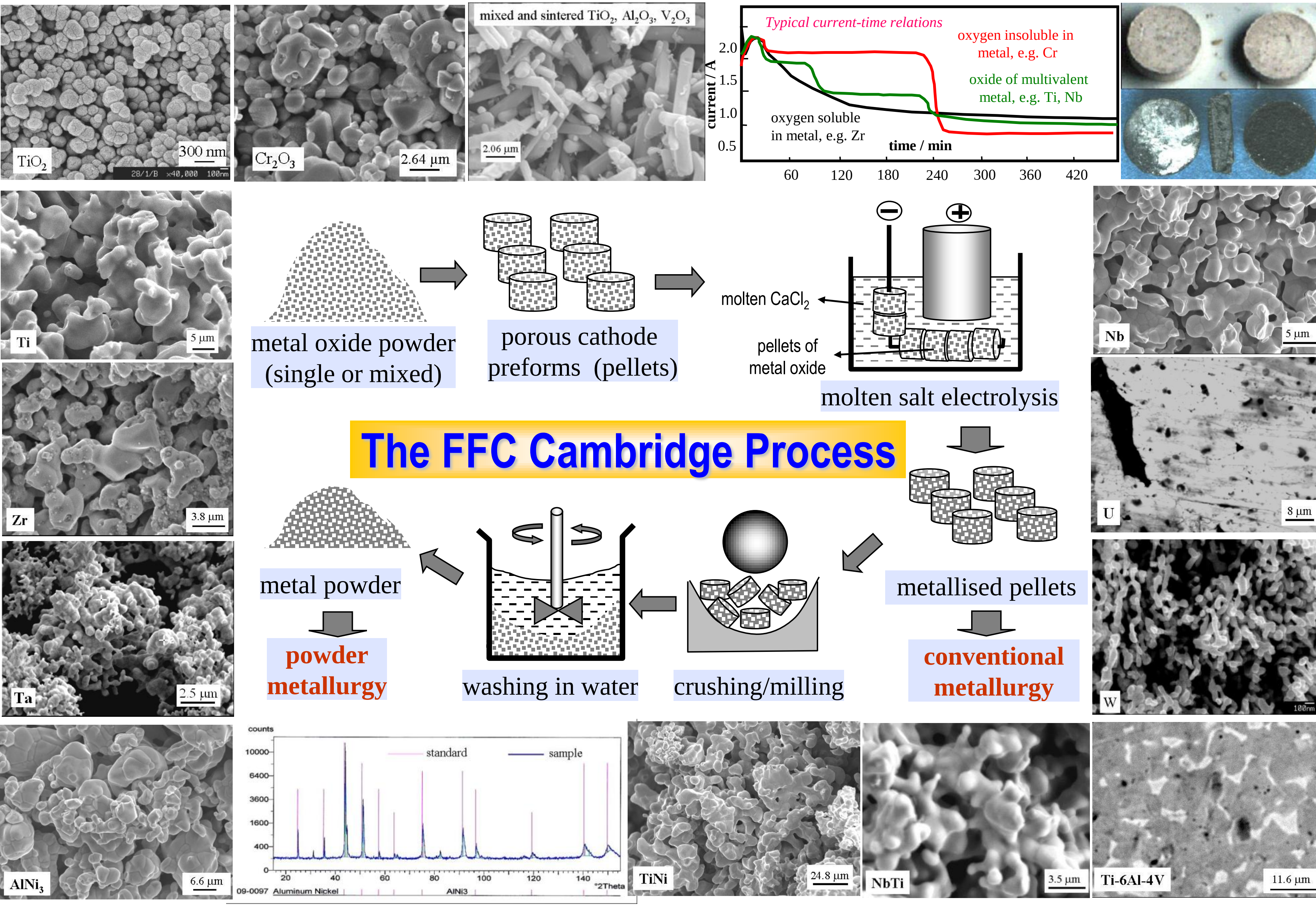
Electro-Reduction of Solid Metal Oxides in Molten Salts ---Thermodynamics

Table 1 Gibbs free energy change (ΔG) and decomposition voltage (E_d) of typical oxides at 900 °C and melting point of the compounds, $(m.p.)_{comp}$, and the metals $(m.p.)_m$

Reaction	ΔG/kJ	V_d/V	$(m.p.)_{comp}$/°C	$(m.p.)_m$/°C
$LiCl(l) = Li(l) + 0.5Cl_2(g)$	365.872	3.792	610	181
$CaCl_2(l) = Ca(l) + Cl_2(g)$	667.414	3.459	782	842
$Y_2O_3 = 2Y + 1.5O_2(g)$	1565.120	2.704	2690	1526
$Tb_2O_3 = 2Tb + 1.5O_2(g)$	1534.838	2.651	2410	1359
$Dy_2O_3 = 2Dy + 1.5O_2(g)$	1518.622	2.623	2408	1411
$BeO = Be + 0.5O_2(g)$	494.328	2.562	2578	1287
$Nd_2O_3 = 2Nd + 1.5O_2(g)$	1478.091	2.553	2320	1016
$Pr_2O_3 = 2Pr + 1.5O_2(g)$	1475.931	2.549	2300	931
$La_2O_3 = 2La + 1.5O_2(g)$	1461.984	2.525	2305	920
$CaO = Ca(l) + 0.5O_2(g)$	486.360	2.520	2900	842
$HfO_2 = Hf + O_2(g)$	901.734	2.336	2774	2233
$Li_2O = 2Li(l) + 0.5O_2(g)$	441.317	2.287	1570	181
$UO_2 = U + O_2(g)$	881.835	2.285	2827	1135
$MgO = Mg(l) + 0.5O_2(g)$	440.458	2.283	2830	650
$ZrO_2 = Zr + O_2(g)$	877.558	2.274	2677	1855
$Al_2O_3 = 2Al(l) + 1.5O_2(g)$	1303.568	2.252	2054	660
$TiO = Ti + 0.5O_2(g)$	430.472	2.231	1750	1668
$CeO_2 = Ce + O_2(g)$	846.748	2.194	2400	799
$TiO_2 = Ti + O_2(g)$	732.128	1.897	1800	1668
$SiO_2 = Si + O_2(g)$	700.324	1.815	1710	1414
$B_2O_3(l) = 2B + 1.5O_2(g)$	981.640	1.696	450	2075
$Ta_2O_5 = 2Ta + 2.5O_2(g)$	1533.416	1.589	1880	3017
$V_2O_3(l) = 2V + 1.5O_2(g)$	852.721	1.473	1970	1910
$Nb_2O_5 = 2Nb + 2.5O_2(g)$	1390.475	1.441	1460	2477
$Cr_2O_3 = 2Cr + 1.5O_2(g)$	827.988	1.430	2450	1907
$Ga_2O_3 = 2Ga(l) + 1.5O_2(g)$	708.586	1.224	1725	30
$CO(g) = C + 0.5O_2(g)$	215.491	1.117	−205	4492
$V_2O_5(l) = 2V + 2.5O_2(g)$	1059.364	1.098	685	1910
$CO_2(g) = C + O_2(g)$	396.040	1.026	−57	4492
$FeO = Fe + 0.5O_2(g)$	187.614	0.972	1370	1538
$WO_3 = W + 1.5O_2(g)$	543.804	0.939	1473	3422
$GeO_2 = Ge + O_2(g)$	355.164	0.920	1116	938
$Fe_2O_3 = 2Fe + 1.5O_2(g)$	516.287	0.892	1565	1538
$SnO_2 = Sn(l) + O_2(g)$	338.464	0.877	1630	232
$MnO_2 = Mn + O_2(g)$	308.893	0.800	535	1246
$MoO_3 = Mo + 1.5O_2(g)$	456.796	0.789	795	2623
$NiO = Ni + 0.5O_2(g)$	133.576	0.692	1960	1455
$Co_3O_4 = 3Co + 2O_2(g)$	460.145	0.596	900	1495
$Cu_2O = 2Cu + 0.5O_2(g)$	83.206	0.431	1230	1085

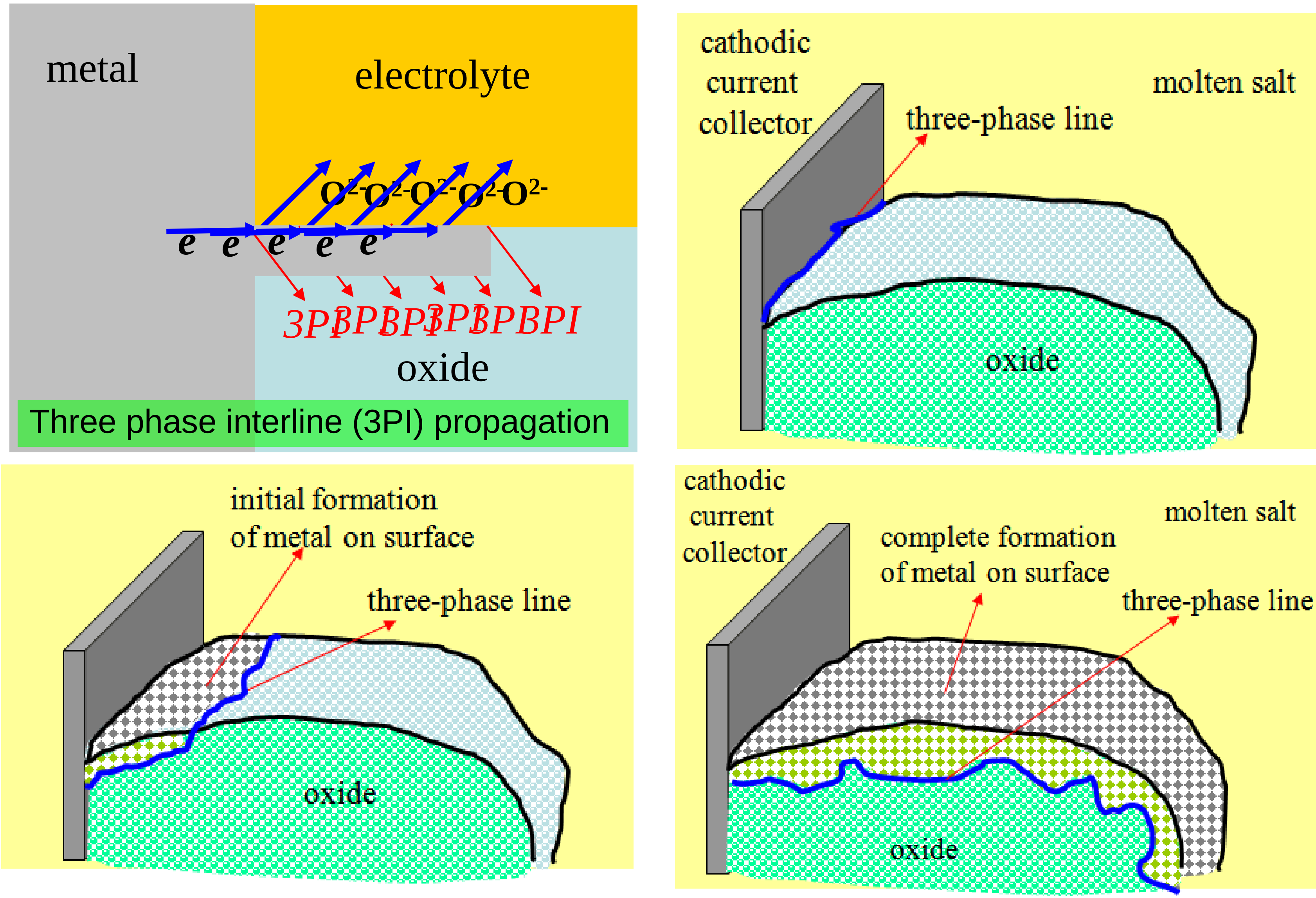
(1) HSC Chemistry

(2) Wang DH, Jin XB, Chen GZ, ***Annu. Rep. Prog. Chem., Sect. C: Phys. Chem.***, 104 (2008) 189-234.



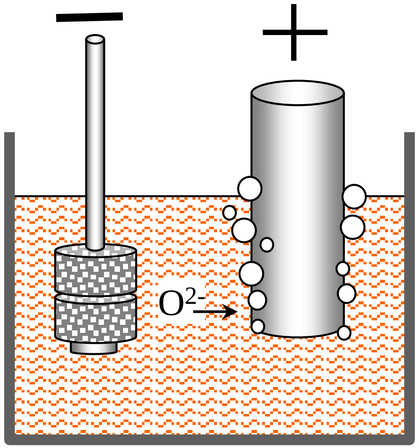
TiO2
300 nm
28/1/B ×40,000 100nm
Cr2O3
2.64 µm
mixed and sintered TiO2, Al2O3, V2O3
2.06 µm
Typical current-time relations
oxygen insoluble in metal, e.g. Cr
oxide of multivalent metal, e.g. Ti, Nb
oxygen soluble in metal, e.g. Zr
current / A
time / min
2.0
1.5
1.0
0.5
60
120
180
240
300
360
420
Ti
5 µm
Zr
3.8 µm
Ta
2.5 µm
metal oxide powder (single or mixed)
porous cathode preforms (pellets)
molten CaCl2
pellets of metal oxide
molten salt electrolysis
The FFC Cambridge Process
metallised pellets
conventional metallurgy
crushing/milling
washing in water
metal powder
powder metallurgy
Nb
5 µm
U
8 µm
W
100nm
AlNi3
6.6 µm
counts
10000
6400
3600
1600
400
0
standard
sample
20
40
60
80
100
120
140
°2Theta
09-0097 Aluminum Nickel
AlNi3
TiNi
24.8 µm
NbTi
3.5 µm
Ti-6Al-4V
11.6 µm

Electrolysis of Insulating Solid Oxide: 3PI Mechanism

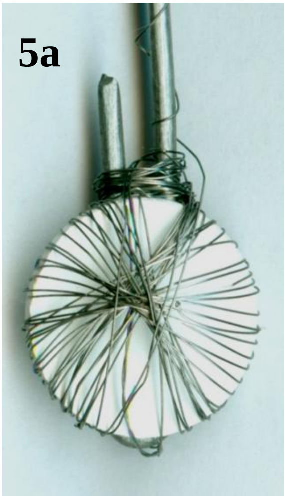


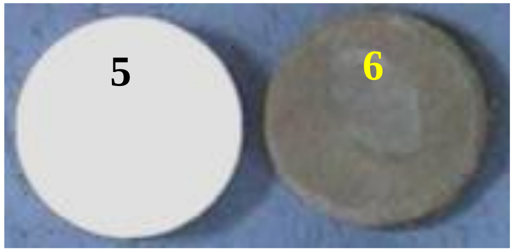
Chen GZ, ***MS6***, Shanghai, Oct. 2001

Electro-Reduced Cylindrical Pellets



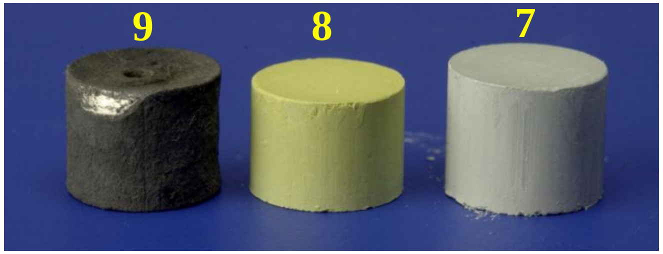
3.0 V, 950°C, molten $CaCl_2$



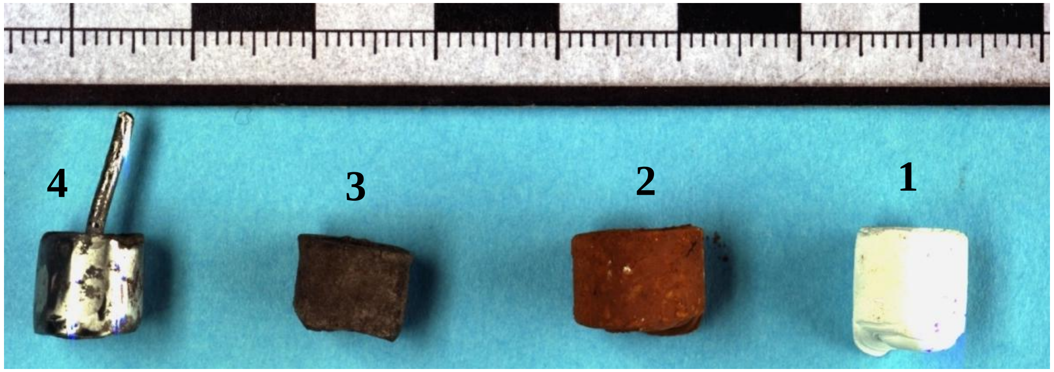


5. Die-pressed TiO_2 pellet.
6. After electrolysis in $CaCl_2$.

M Ma et al, *J. Alloys Compd.* 420 (2006) 37



7. Die-pressed NiO+TiO_2 pellet.
8. After sintering in air (950 °C).
9. After electrolysis in $CaCl_2$



1. Slip cast & sintered TiO_2,
2. Slip cast & sintered mixed TiO_2, Al_2O_3 and V_2O_3

3,4. Electro-reduced in molten $CaCl_2$ at 3.1 V, 950°C

Product purity: > 99.8%

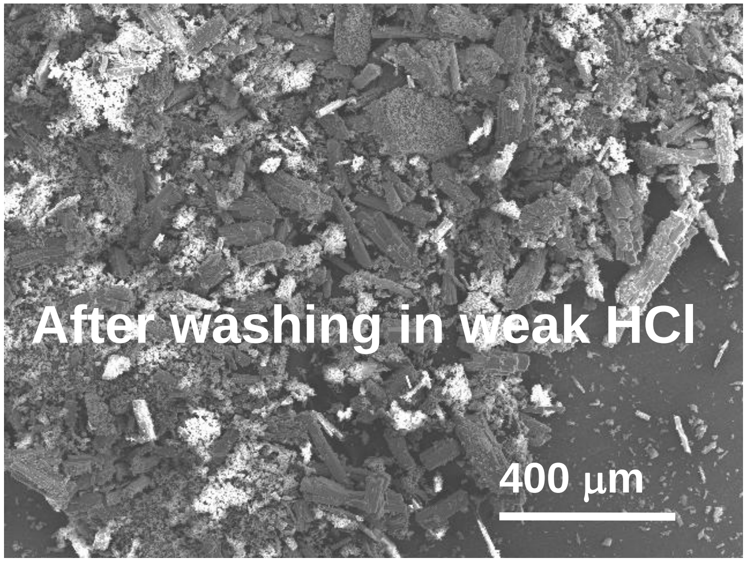
Main impurity: O < 2000 ppm

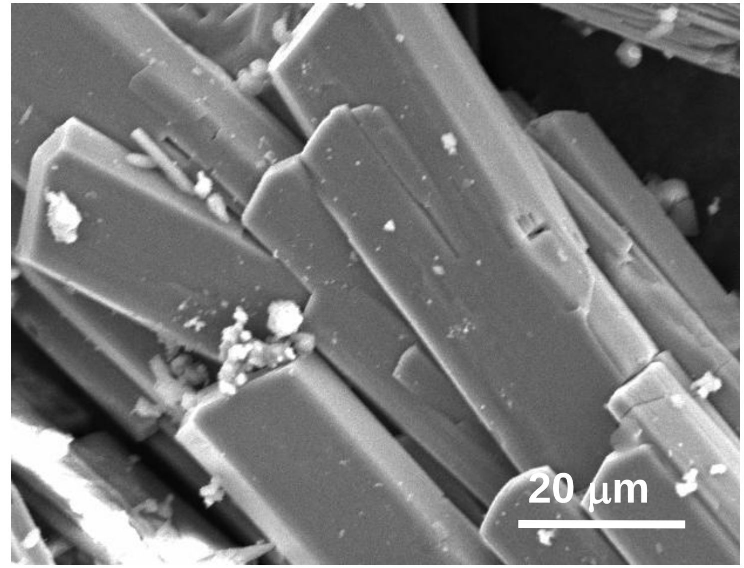
E.C.: < most, if not all, exiting technologies.

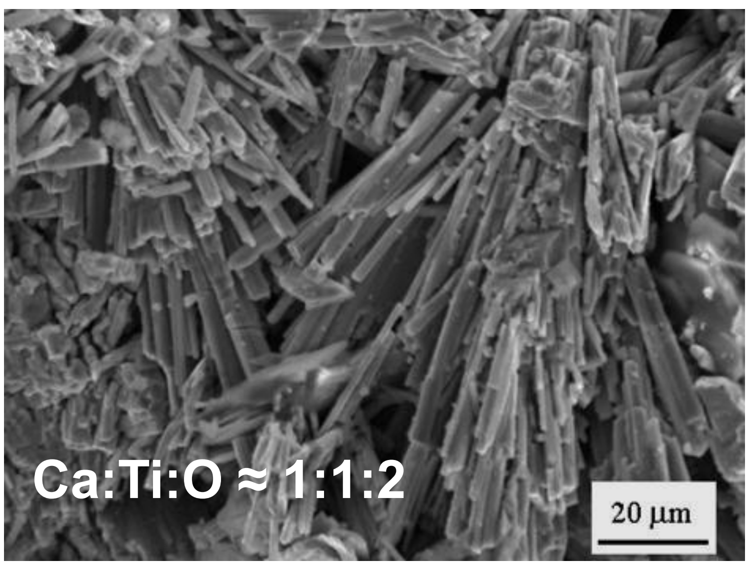
C.E.: ☹ 10 ~ 90 % ☺

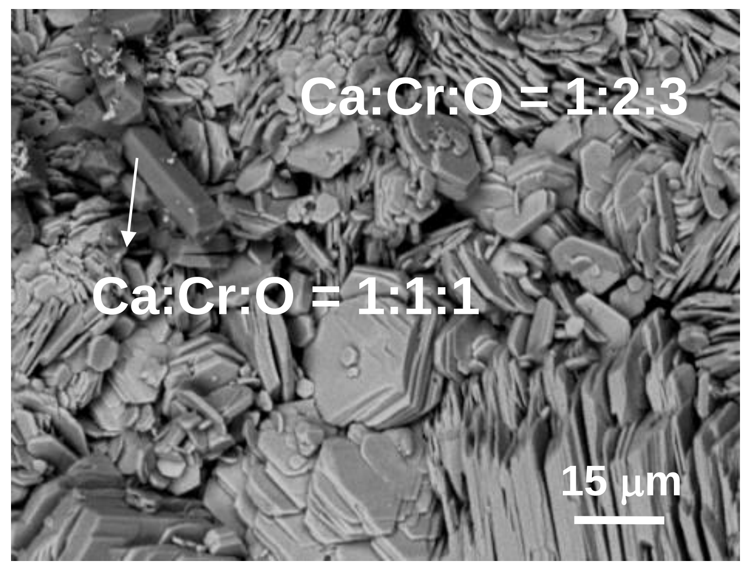
Intermediate Products from Partial Electro-reduction

$Ca_xM_yO_z$ crystallites in partially reduced oxide pellets









In situ Perovskitisation

Chen, Fray, ***J. Electrochem. Soc.*** 149 (2002) E455;

Chen, Fray, ***Light Metals 2004***, (2004) 881.

Chemical reaction due to CaO saturation

$M_xO_y + CaO\ (Ca^{2+} + O^{2-}) = CaM_xO_{y+1}$

Electro-intercalation, or -chemisorption

$M_xO_y + Ca^{2+} + 2e = CaM_xO_y$;

$M_xO_y + Ca^{2+} + 2e = M + CaM_{x-1}O_y$;

$M_xO_y + Ca^{2+} + 4e^- = M + O^{2-} + CaM_{x-1}O_{y-1}$

....

Jiang et al, ***Angew. Chem. Int. Ed.***, 45 (2006) 428.

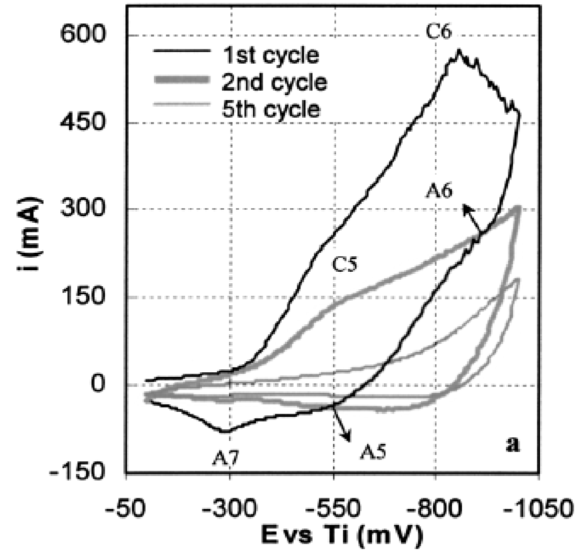
Chemical perovskitisation

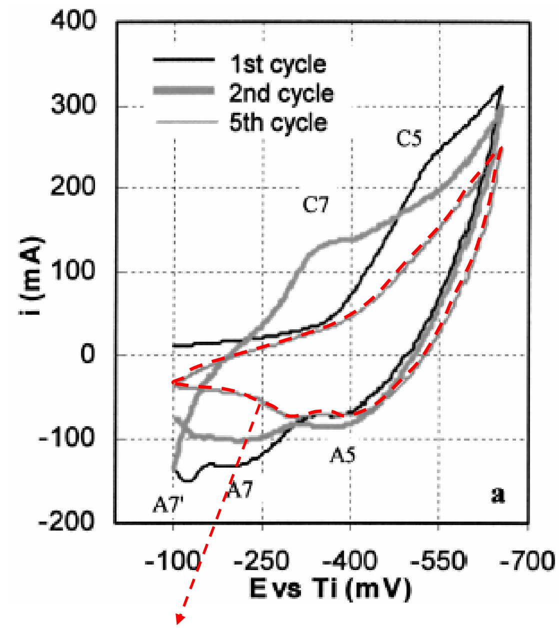
$TiO_2 + 2\alpha\ e \Rightarrow TiO_{2-\alpha} + \alpha\ O^{2-}\ (0 < \alpha \le 2)$

$TiO_x + \alpha\ O^{2-} + \alpha\ Ca^{2+} \Rightarrow Ca_\alpha TiO_{x+\alpha}\ (1 < x \le 2)$

Electrochemical perovskitisation

$TiO_x + \beta\ Ca^{2+} + 2\ \beta\ e \Leftrightarrow Ca_\beta TiO_x\ \ (0 \le \beta < 1)$



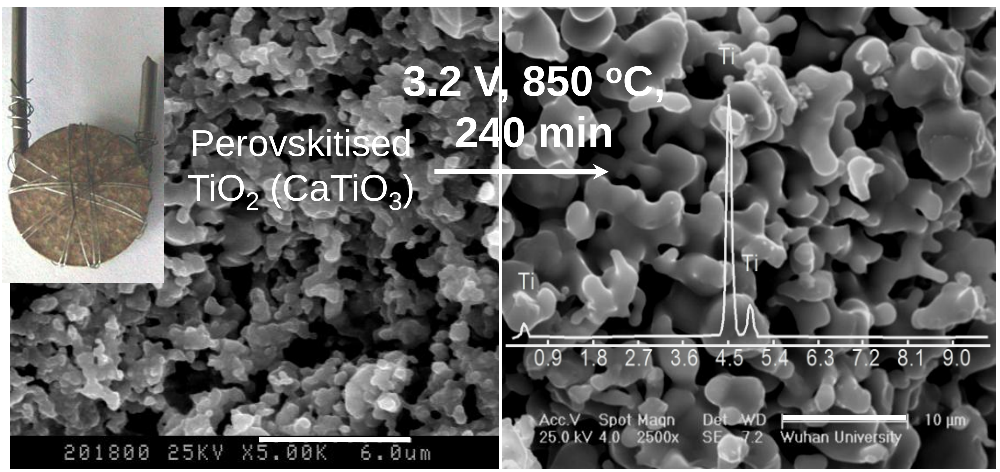


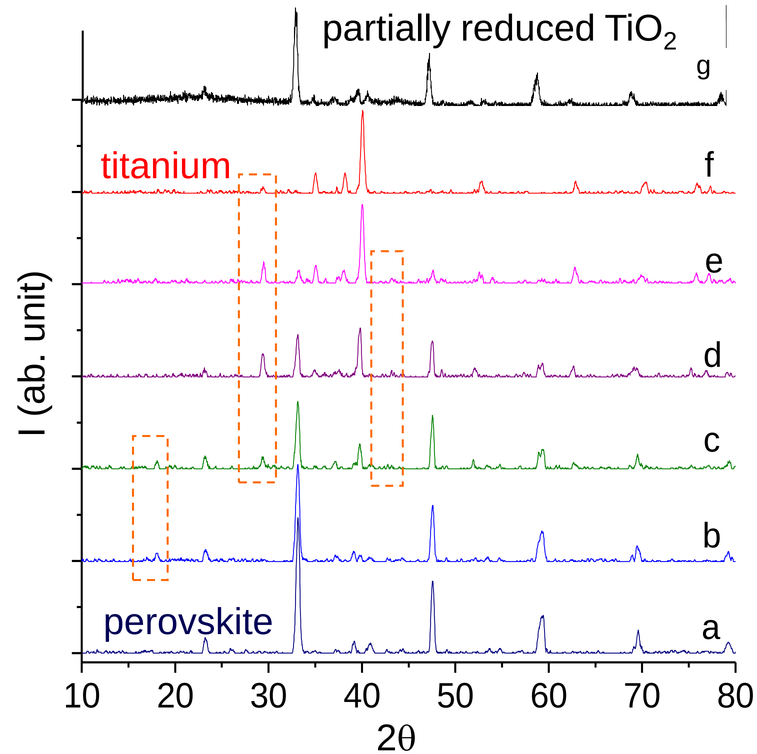
reproducible CV

Fast Electro-Reduction of Pre-Perovskitised TiO_2

Pre-Perovskitisation increases electrolysis speed and efficiency (~50%)。

$$Ca_{\delta}TiO_{2+\delta}\,(TiO_2 + \delta CaO) + 4e \Rightarrow Ti + \delta CaO + O_2$$





XRD patterns. (a) Synthetic $CaTiO_3$. (g) partially reduced TiO_2. (b-f) After electrolysis in molten $CaCl_2$ at 3.2 V and 850°C for 10 (b), 30 (c), 60 (d), 120 (e) and 240 min (f).

XRD analysis of different phases in electrolysis products

TiO_2 900 °C	3.0 V, 0.5 h	Ca_xTiO_y (81.3 %) + Ti_2O_3 (18.7 %)
	3.0 V, 2 h	Ca_xTiO_y (83.7) + Ti_2O_3 (10.6) + T_3O_5 (5.7)
	3.0 V, 4 h	Ca_xTiO_y (89.9) + TiO (11.1)
$CaTiO_3$ 850 °C	2.8 V, 5 h	Ti (*87.2*) + **X** (*12.8*)
	2.6 V, 5 h	Ti (*51.8*) + Ca_xTiO_y (*38.8*) + **X** (*9.4*)
	2.4 V, 15 h	Ti (*50.1*) + Ca_xTiO_y (*37.7*) + **X** (*12.2*)

Jiang et al, ***Angew. Chem. Int. Ed.***, 45 (2006) 428.

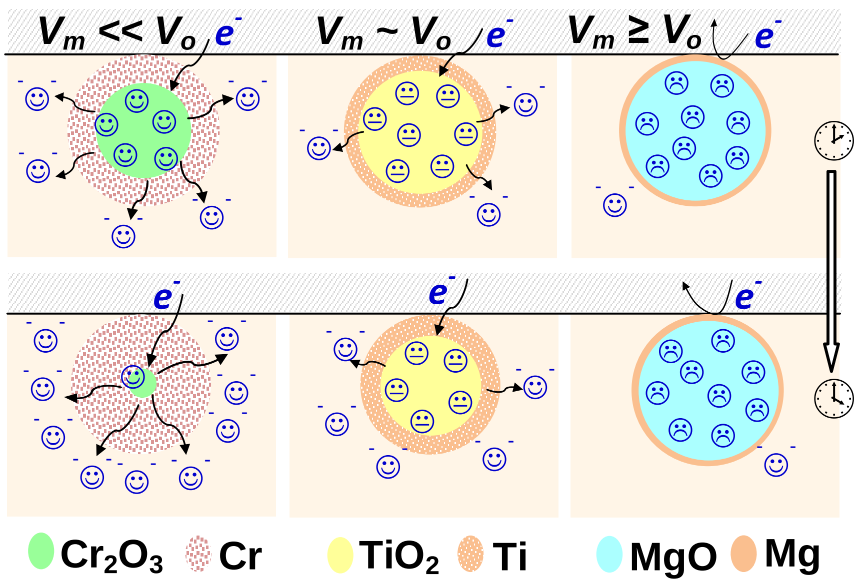
~50% improvement in E.C. and C.E.

Molar Volume Ratios of Selected Metal/Oxide Couples

M / MO_x	Ta / Ta_2O_5	Cr / Cr_2O_3	Zr / ZrO_2	Al / Al_2O_3	Mg / MgO	Ti / TiO_2	Ti / Ti_2O_3	Ti / TiO	Ti/ Ti_2O
V_m/V_o	0.40	0.50	0.66	0.78	**1.25**	0.63	0.74	0.91	≥ 1 ?

Pilling-Bedworth Equation: $$\frac{V_m}{V_o} = \frac{M_o/(n\rho_o)}{M_m/\rho_m}$$

n = 1 for TiO_2 and MgO,
n = 2 for Cr_2O_3 and Ta_2O_5,
n = 3 for Fe_3O_4



W Li et al, *Angew. Chem. Int. Ed.* 49 (2010) 3203.

No successful electro-reduction of MgO to Mg metal is reported.

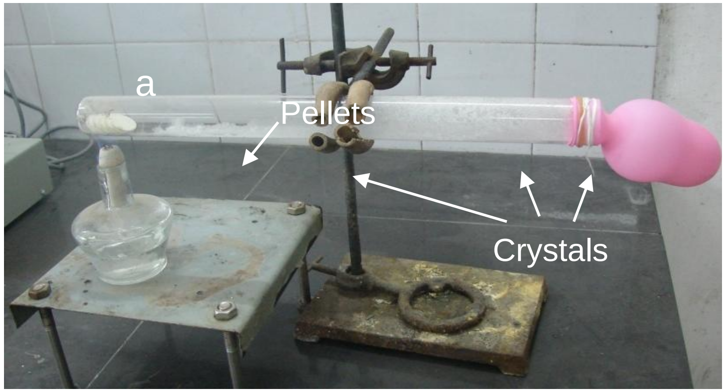
S Tan et al, *J. Alloy Compd.* 504 (2010) 134.

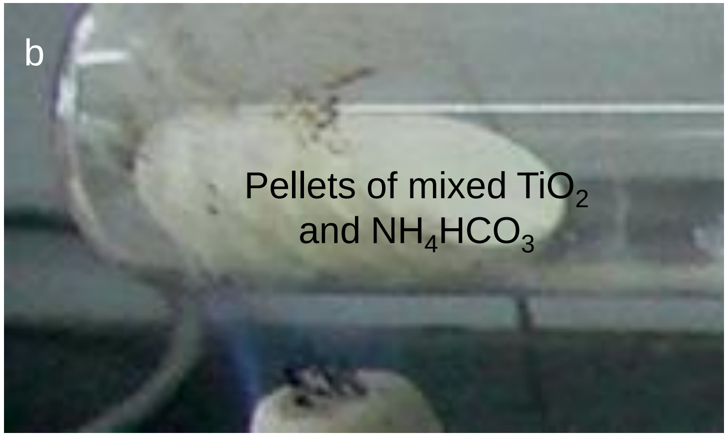
Apart from V_{Mg}/V_{MgO} > 1, Mg metal does not dissolve oxygen,

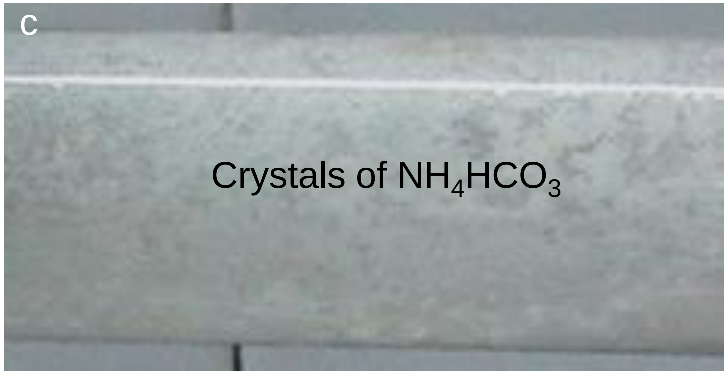
but Ti metal does.

Smaller particle and greater metal / electrolyte interface are needed to promote O transfer.

Recyclable NH_4HCO_3 for Highly Porous TiO_2 Precursor

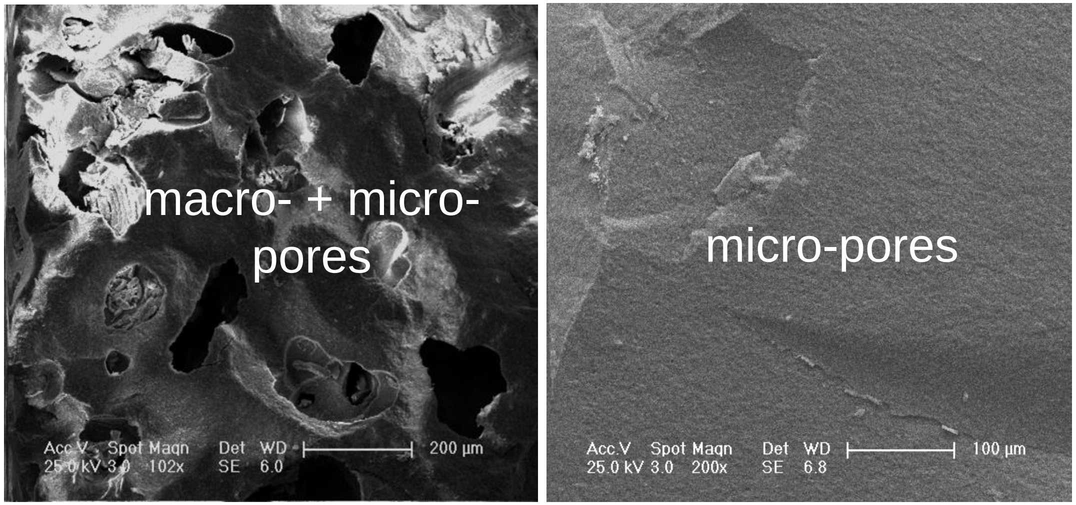






$$NH_4HCO_3 \xrightleftharpoons{86\ ^oC,\ 1atm} NH_3 + CO_2 + H_2O$$

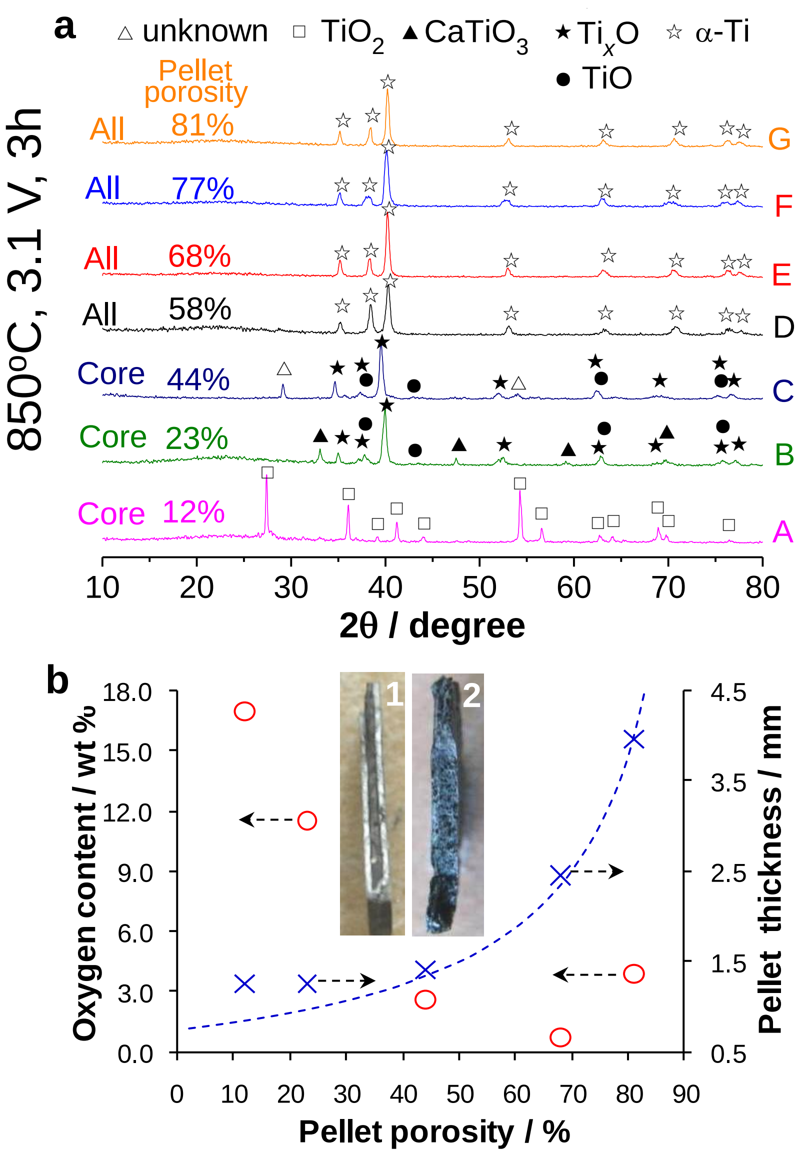
Recovery of NH_4HCO_3 > 97%



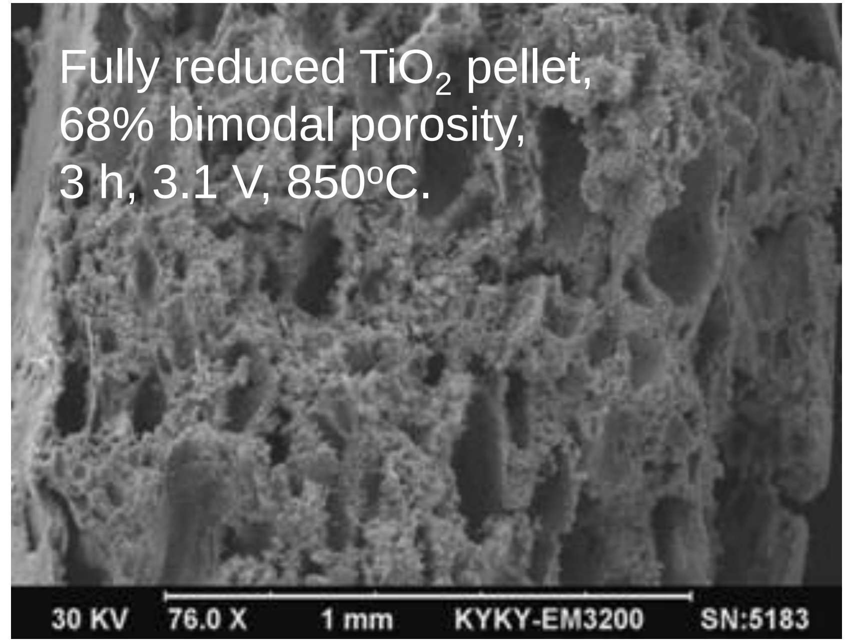
SEM images of TiO_2 pellet prepared with (left) and without (right) using NH_4HCO_3 as fugitive porogenic agent.

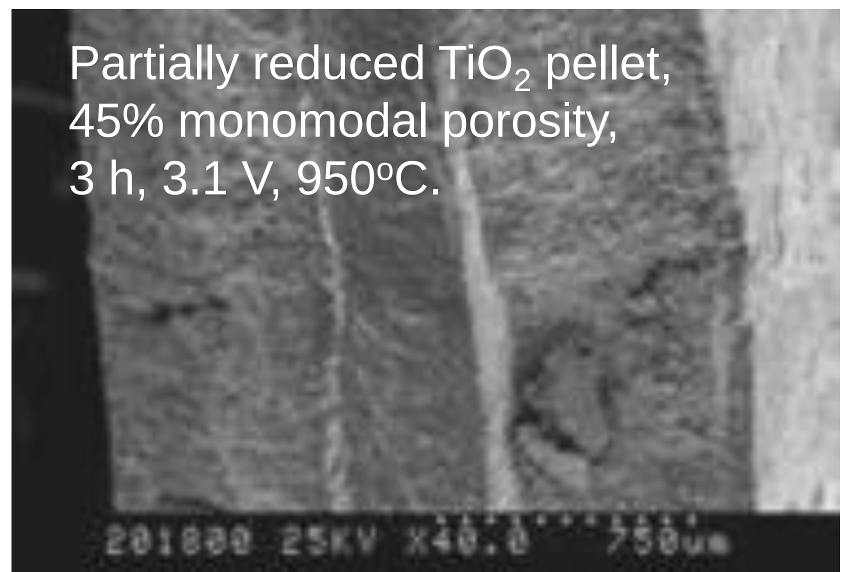
W Li et al, *Angew. Chem. Int. Ed.* 49 (2010) 3203.

Fast Electro-Reduction of Highly Porous TiO_2 Precursor



W Li et al, *Angew. Chem. Int. Ed.* 49 (2010) 3203.



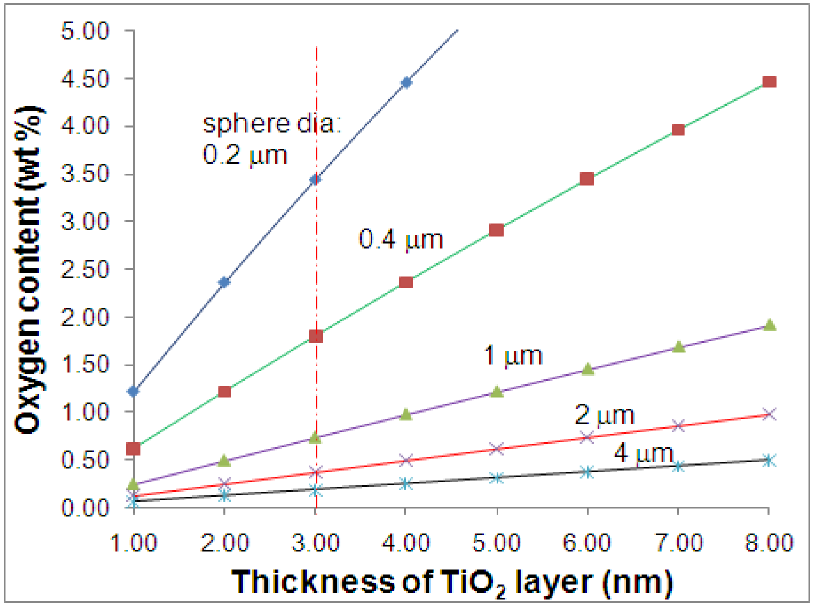


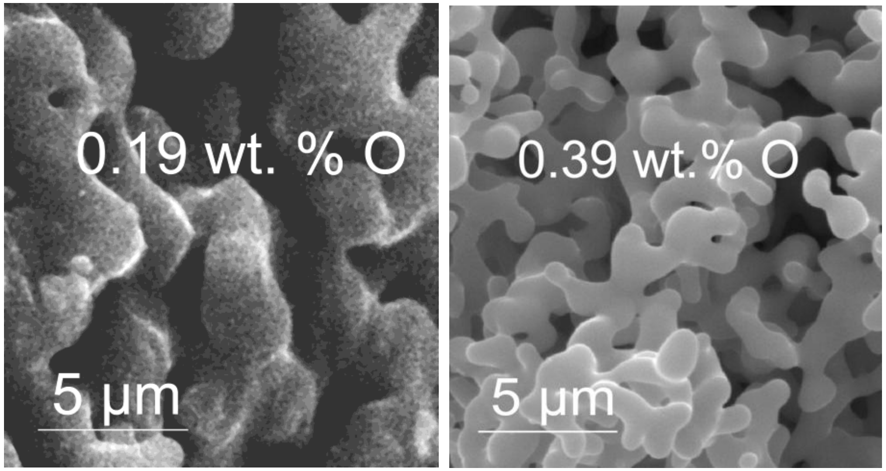
Oxygen content vs. particle size: Surface oxide layer

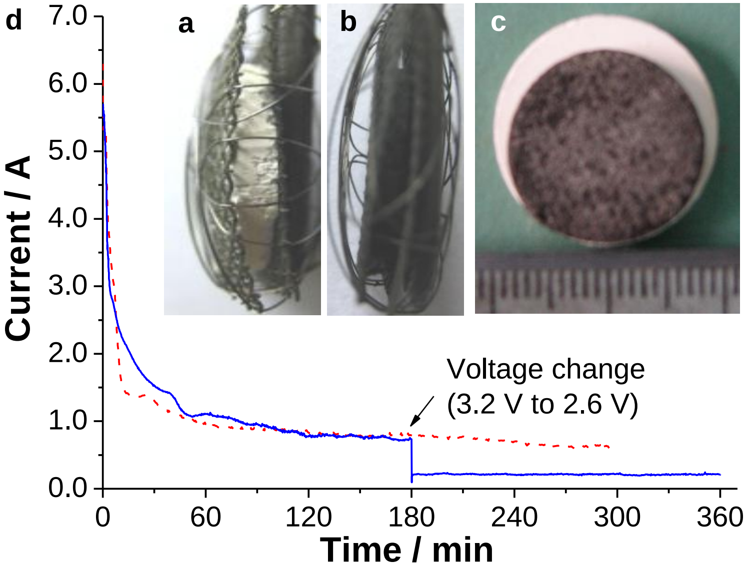
Product oxygen content & process efficiency, for electrolysis of TiO_2, 68% porosity, 850 ºC.

Electrolysis conditions	Oxygen content (wt %)	Current efficiency (%)	Energy consumption (kWh/kg-Ti)
3.0 V, 3 h	1.45	54.4	12.3
3.2 V, 3 h	0.68 [a]	36.3	19.2
3.2 V, 5 h	0.39	28.7	24.9
3.2 V, 3 h + 2.6 V, 3 h	0.19	32.3	21.5

[a] Average of five analyses with maximum error = ±0.35.



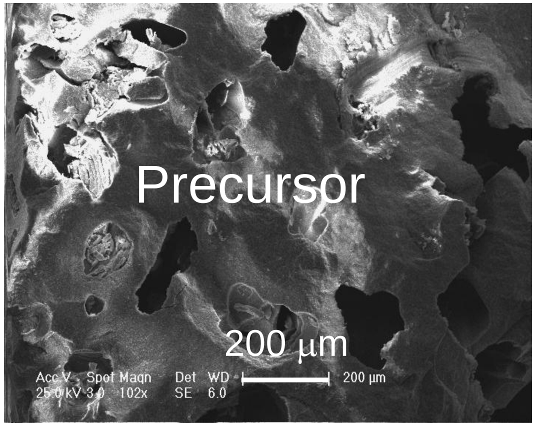




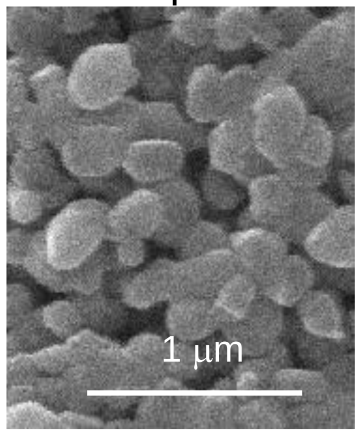
W Li et al, *Angew. Chem. Int. Ed.* 49 (2010) 3203.

Macro-Micro-Bimodal Porosity in Precursor and Product

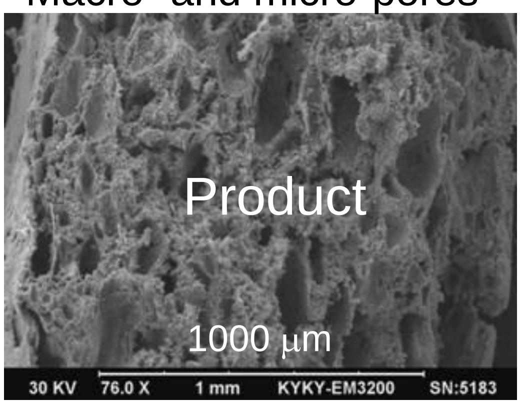
Macro- and micro-pores



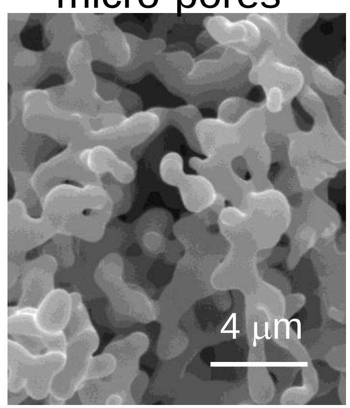
micro-pores



Macro- and micro-pores



micro-pores



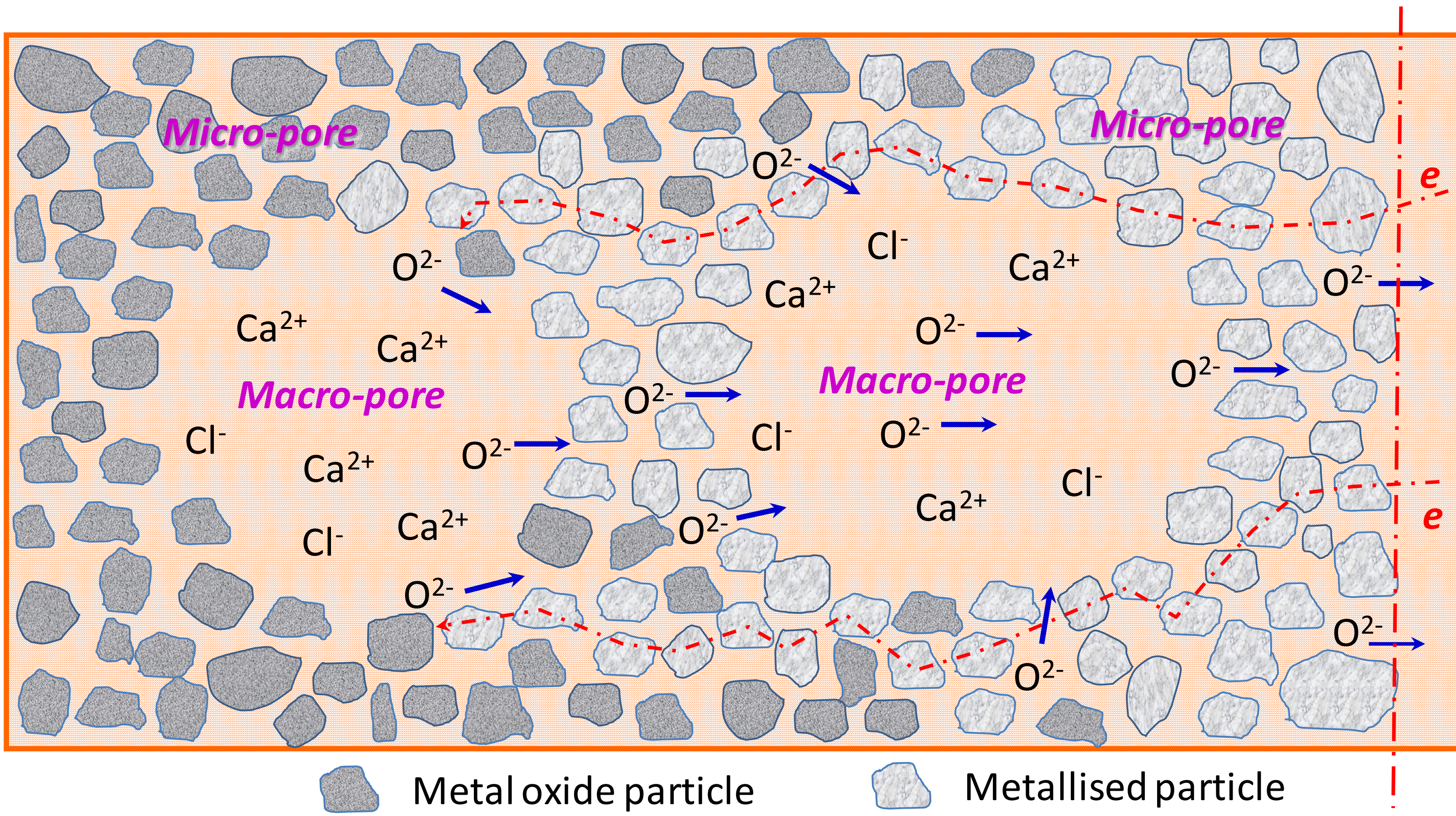
The macro-pores are **several million** times larger than the micro-pores in volume:

↓

Local molten salt reservoirs for avoiding saturation of O^{2-} ions and in situ perovskitisation.

W Li et al., ***J. Rare Earths***, 29 (Spec. Issue) (2011) 1-7.

Enhanced transfer of O^{2-} ions in macro-micro-bimodal pores

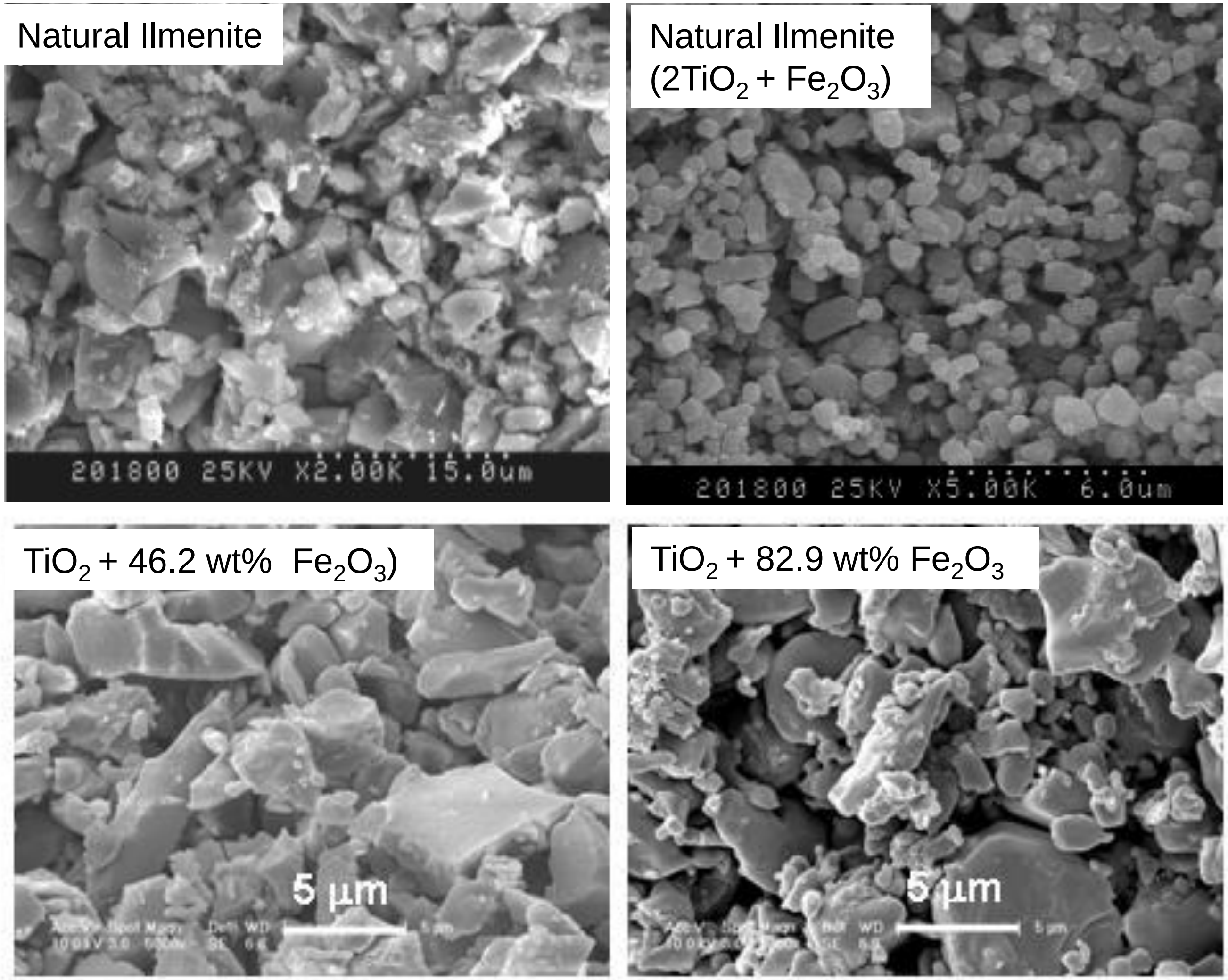


Avoidance of saturation of O^{2-} ions and of formation of perovskites.

Macro-pores: D ~ 10^{-5} cm^2/s *vs.* Micro-pores D ~ 10^{-7} cm^2/s

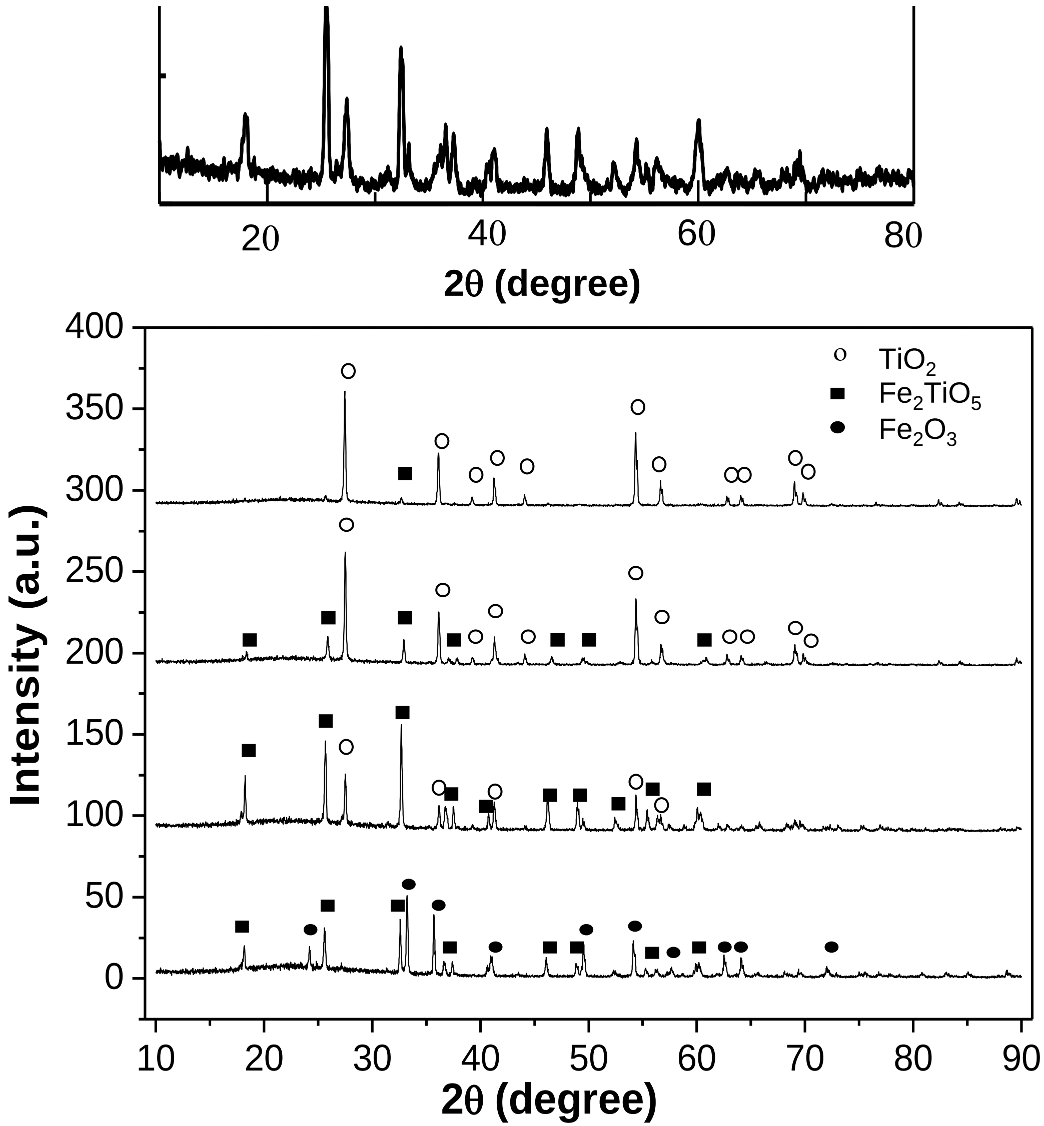
W Li et al., ***J. Rare Earths***, 29 (Spec. Issue) (2011) 1-7.

Natural Ilmenite and mixed TiO_2-Fe_2O_3: SEM



All SEM images of were taken from ground powders. The mixed Fe_2O_3 and TiO_2 samples were prepared by firing at 1300 ^oC and re-milling.

Natural ilmenite and mixed TiO_2-Fe_2O_3: XRD



A: natural ilmenite

B: 1.71 wt % Fe_2O_3

C: 13.1 wt % Fe_2O_3

F: 46.2 wt % Fe_2O_3

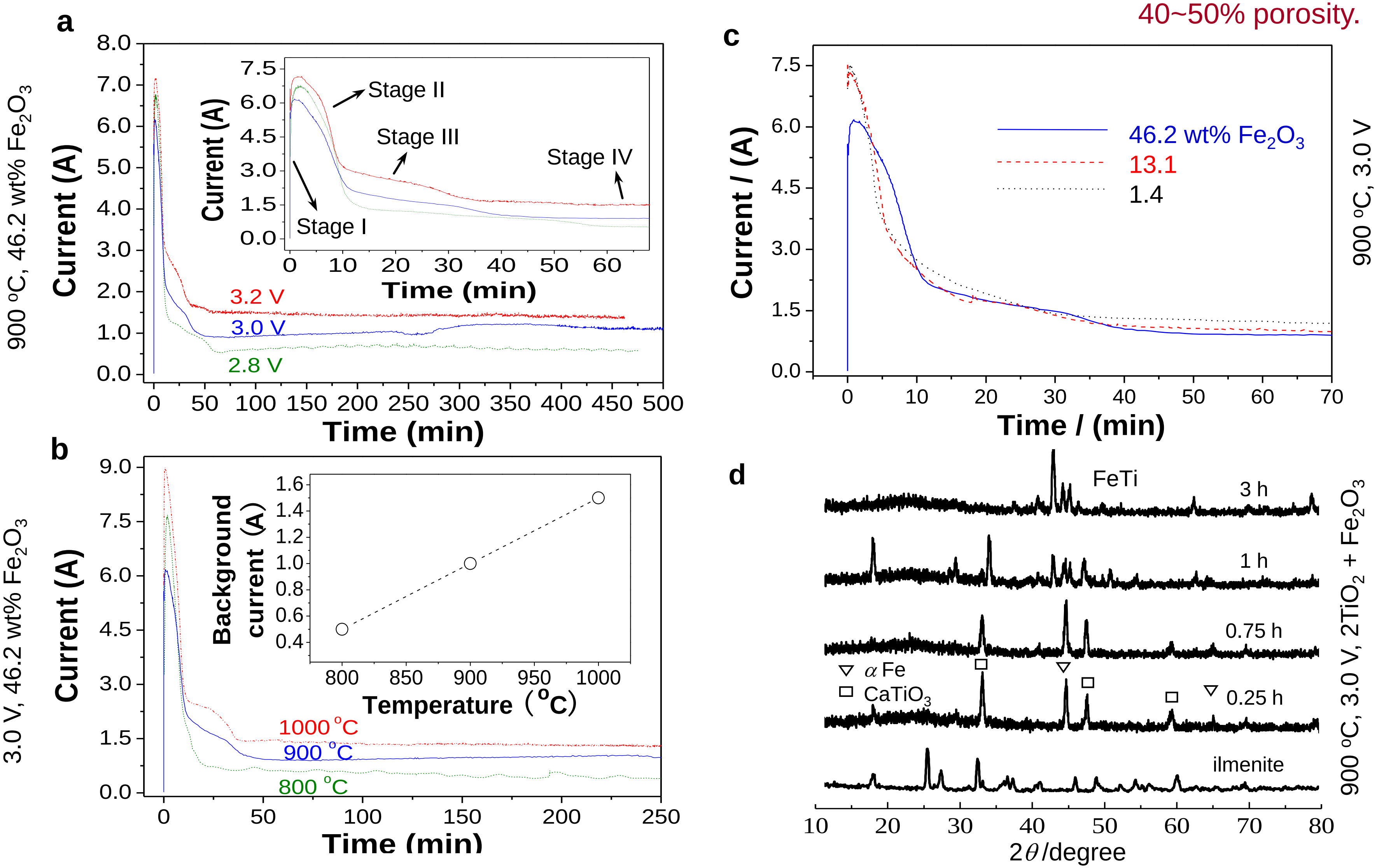
E: 82.9 wt % Fe_2O_3

All patterns were obtained from ground powders. The mixed Fe_2O_3 and TiO_2 samples were prepared by firing at 1300 ^oC and re-milling.

Li GM, Jin XB, Wang DH, Chen GZ, ***J. Alloy Compd.***, 428 (2009) 320-327.

Electrolysis of mixed TiO_2-Fe_2O_3 in Molten $CaCl_2$

Pellet: 2mm th.; 20 mm dia.; 3~5 g; 40~50% porosity.

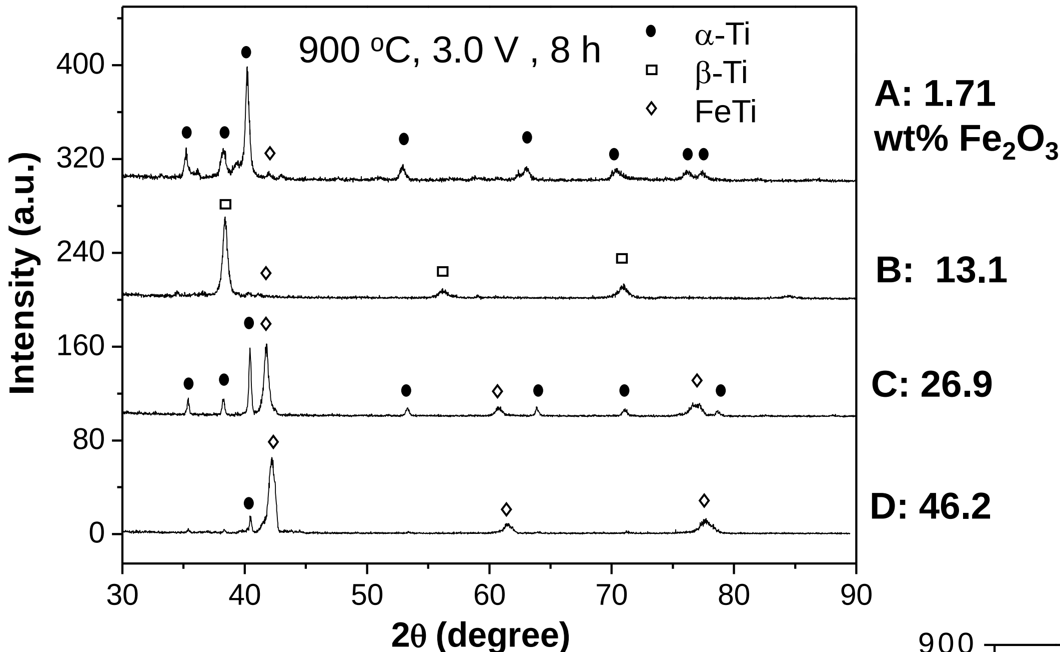


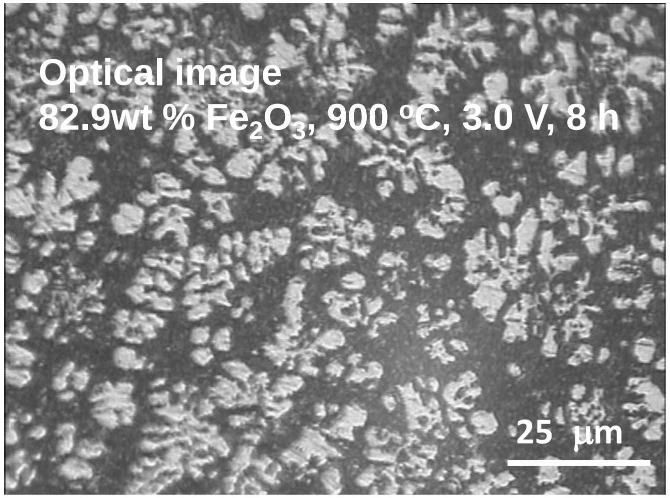
GM Li et al, ***J. Alloy Compd.***, 428 (2009) 320.

M Ma et al, ***Chem.-Eur. J.*** 12 (2006) 5075-5081

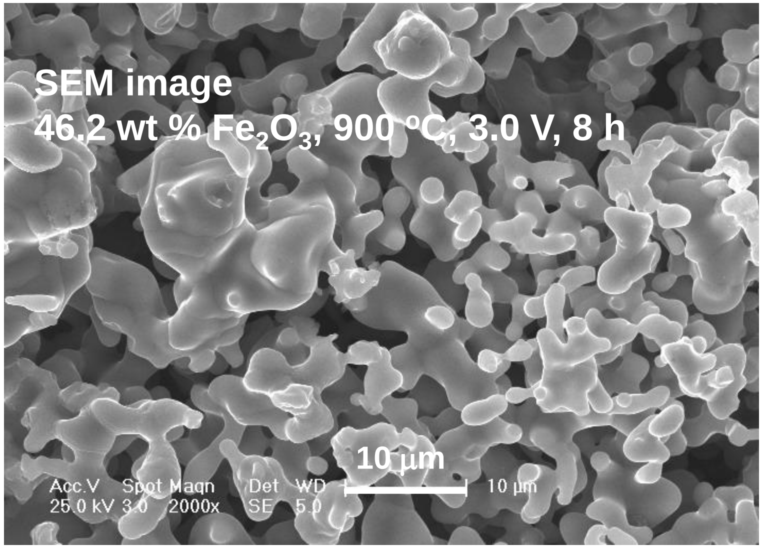
$$TiO_2 + Fe_2O_3 \rightarrow Fe + CaTiO_3 \rightarrow Fe + TiO \rightarrow FeTi$$

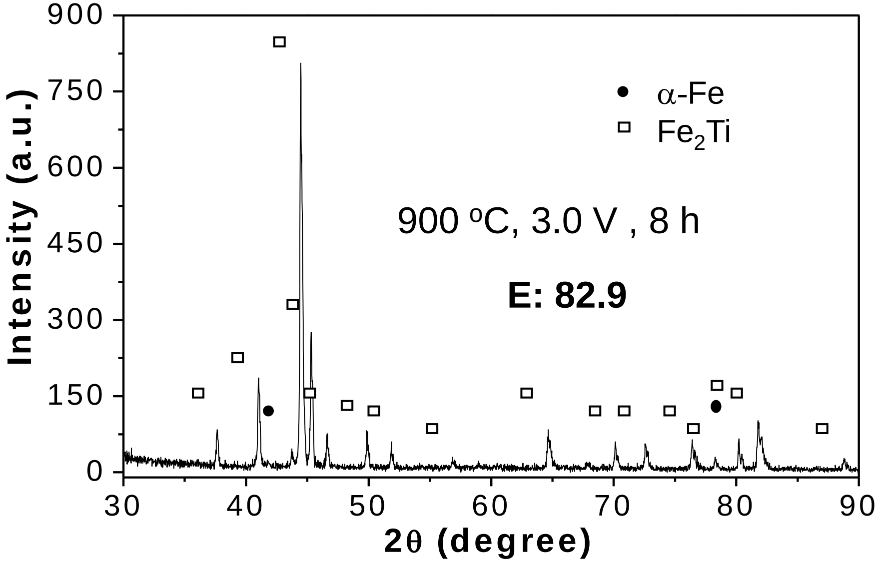
Electrolysis of mixed TiO_2-Fe_2O_3 in Molten $CaCl_2$





Arc-melted ingot, Fe_2Ti dendrite in α-Fe





Properties of Electrolytic Fe-Ti Alloys

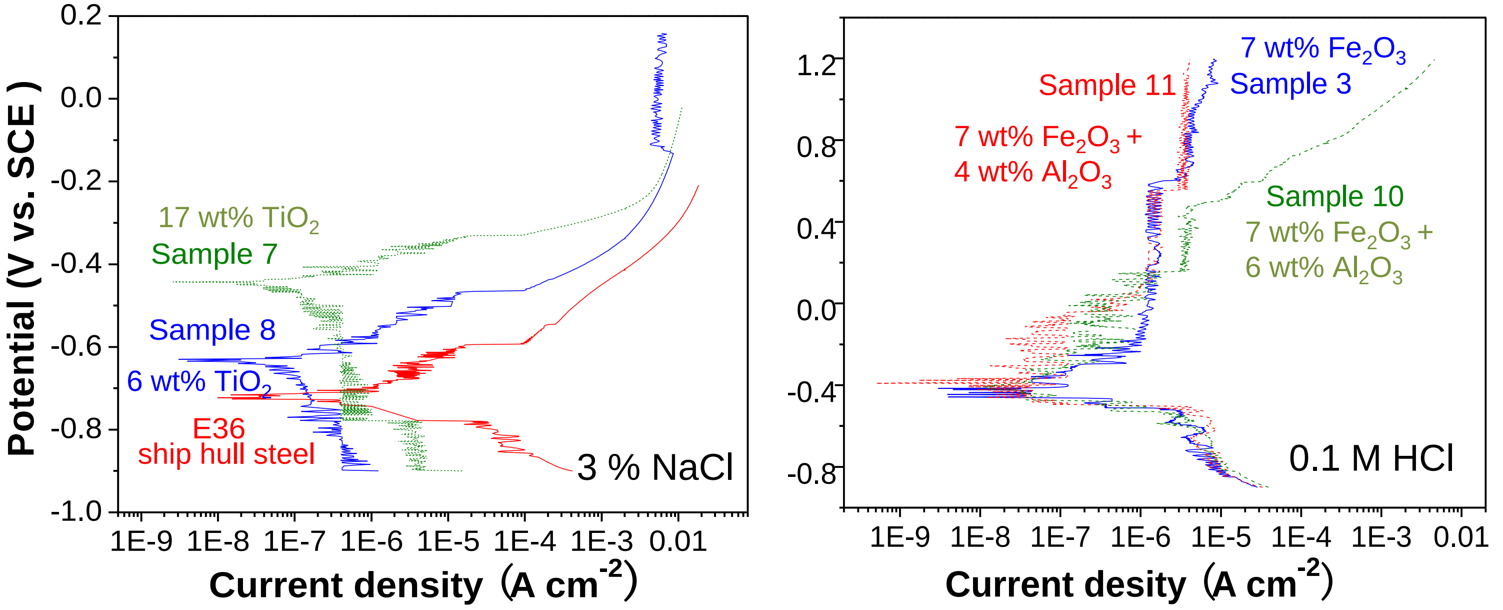
Processing

As-prepared FFC Fe-Ti powers/pellets < ball milling; cold pressing / arc-melted ingots → bulk properties.

Hardness

Content of Fe_2O_3 (mol %)	0	0.9	2.2	3.6	15-50	70.8	89.2
VHN	120	389	583	687	> 900	399	237

Resistance to corrosion

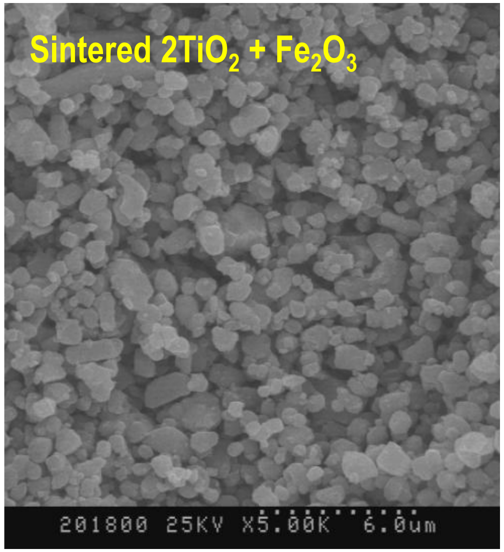


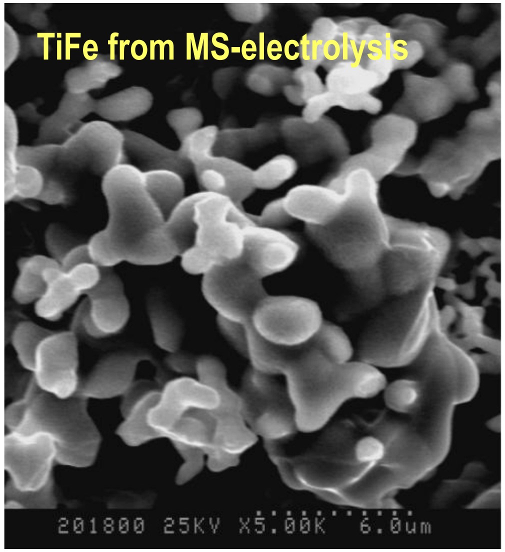
Potential for Production of Ti-Fe-Ni H_2 Storage Alloys (HAS)

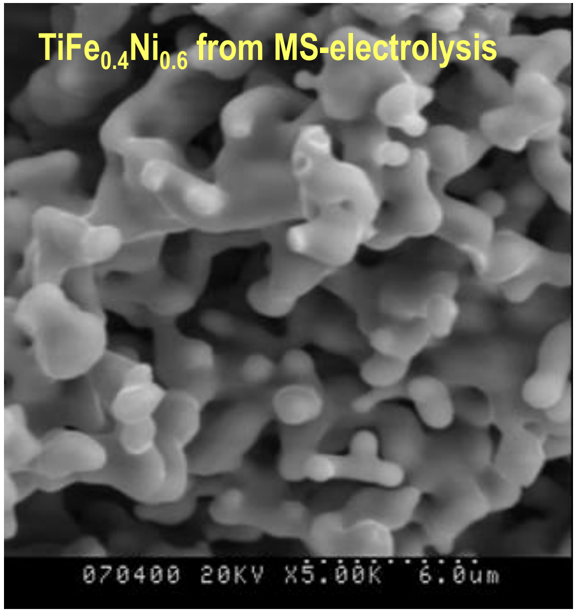
2010 world energy need: $2x10^{14}$ kWh/yr
If ¼ from H_2: $1.3\sim1.9x10^{12}$ kg H_2 /yr
HSA need (5wt%): **$3\sim5x10^{10}$ kg**

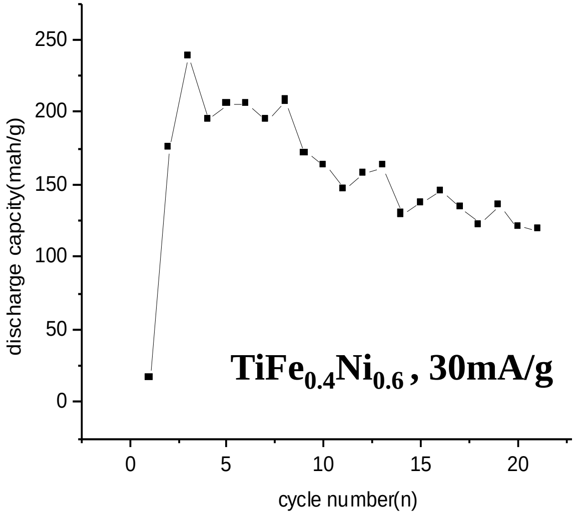
World production
Steel: $\sim1.1x10^{12}$ kg /yr
Aluminium: $\sim2x10^{11}$ kg/yr
Titanium: $\sim1.5x10^{8}$ kg/yr

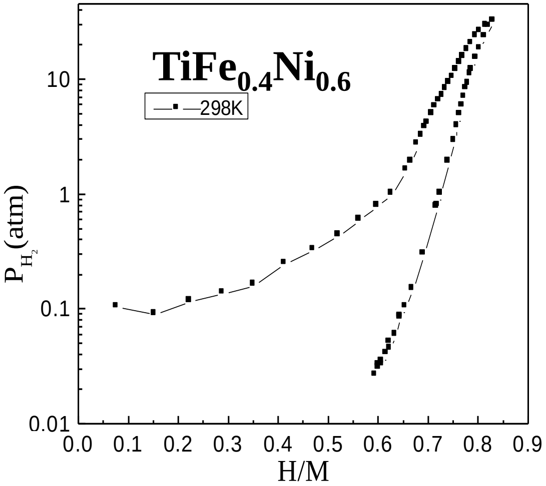
The cheapest HSA from existing method:
TiFe ~ \$10 /kg ($FeTiO_3$: ~\$0.05/kg)









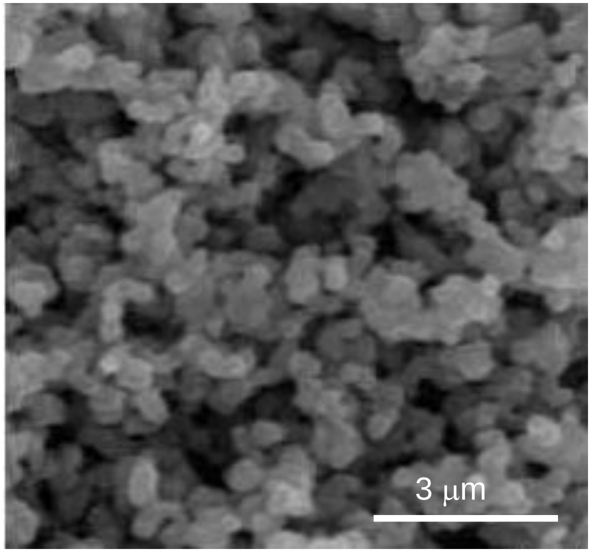


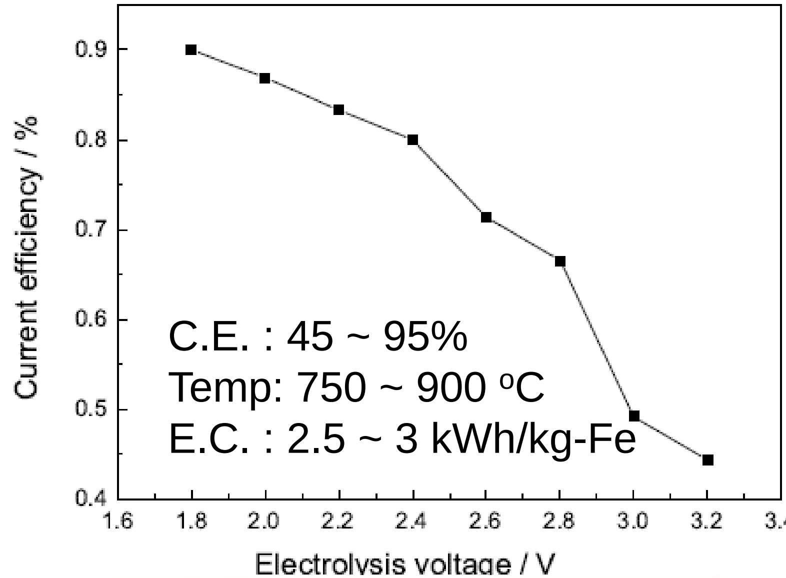
3V, 900°C, 8hrs. C.E.: 75%； E.C. : 7.9 kWh/kg-alloy.

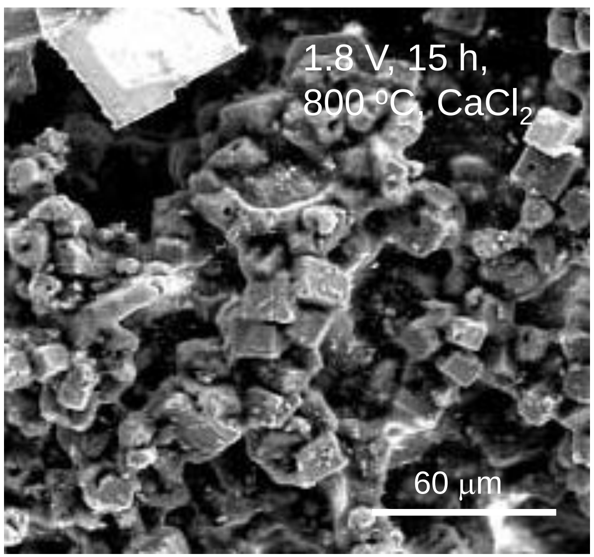
M Ma et al, ***Chem.-Eur. J.*** 12 (2006) 5075-5081

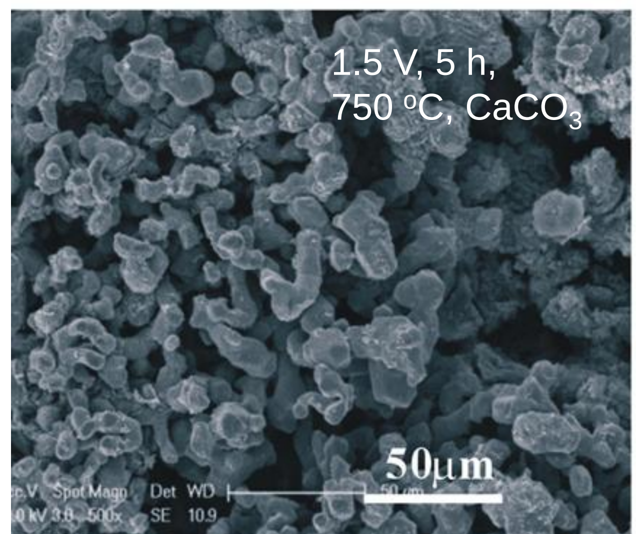
Lab products performed better in thermal / electrochemical tests than HSAs from other methods.

FFC Steel





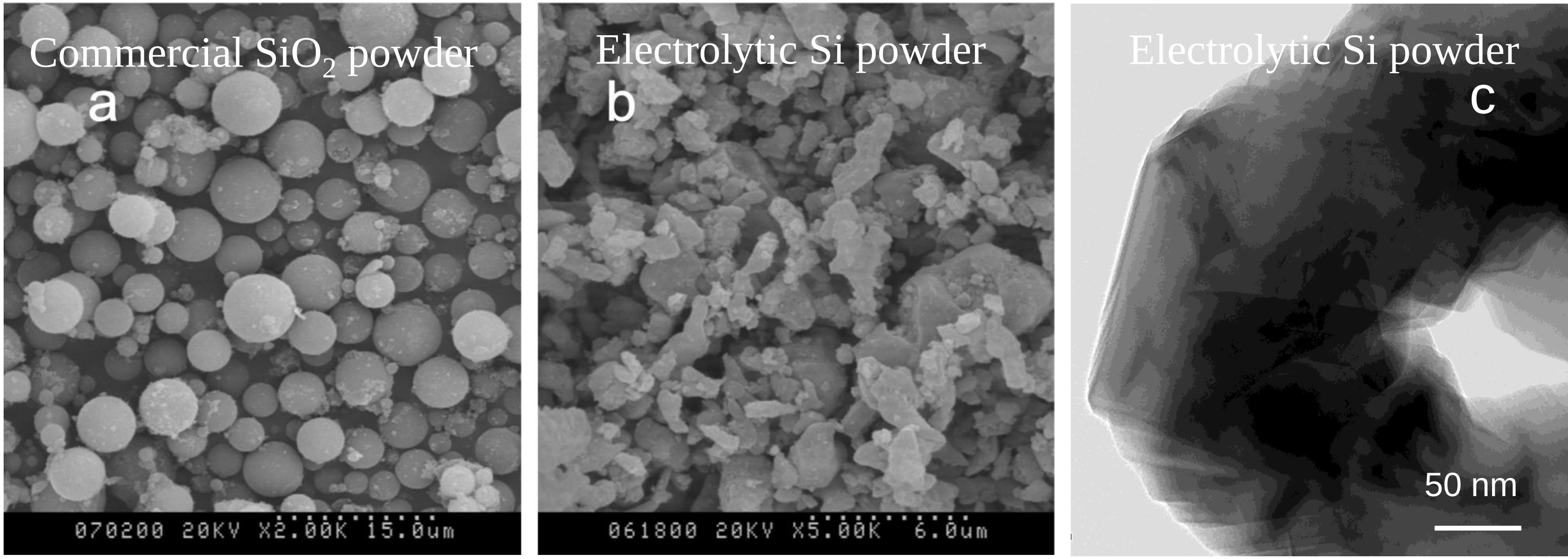


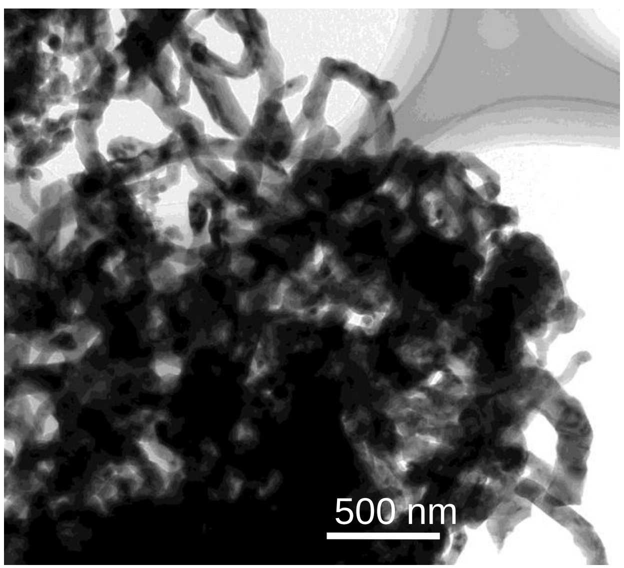


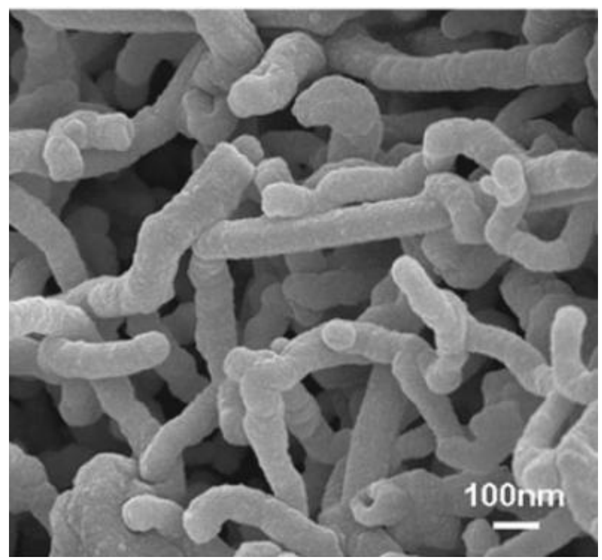
Li GM, Wang DH, Chen Z, ***J. Mater. Sci. Technol.***, 25 (2009) 767

HY Yin, Wang DH et al ***Electrochem. Commun.***, 13 (2011) 1521.

FFC Silicon







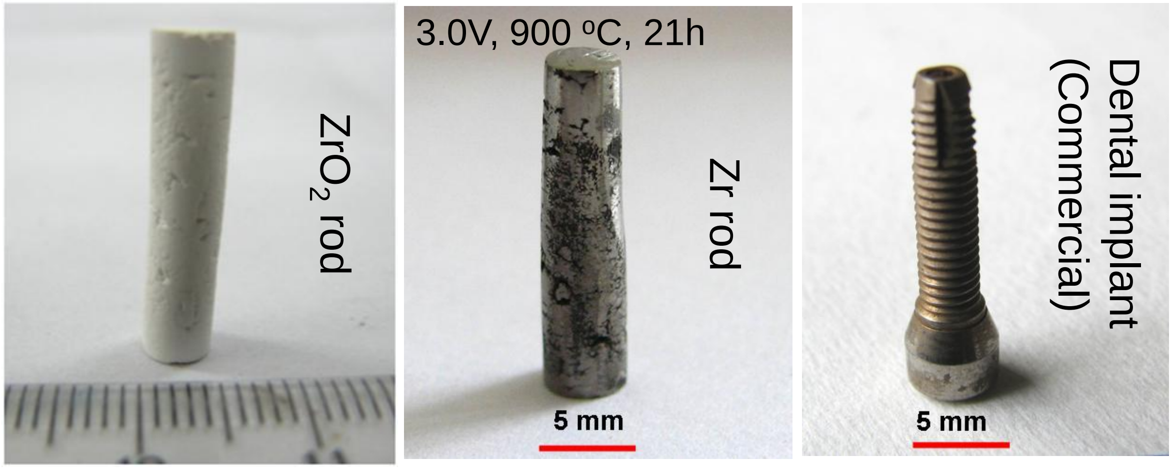
Purity: > 99.9 %
C.E.: 70~90 %
E.C.: 11~13 kWh/kg-Si

Xiao and Wang *et al. Unpublished Results*, Wuhan & Nottingham Universities (2007)

JY Yang *et al.* ***Chem. Commun.***, 2009, 3273

Near-Net-Shape Products: Dental Implant

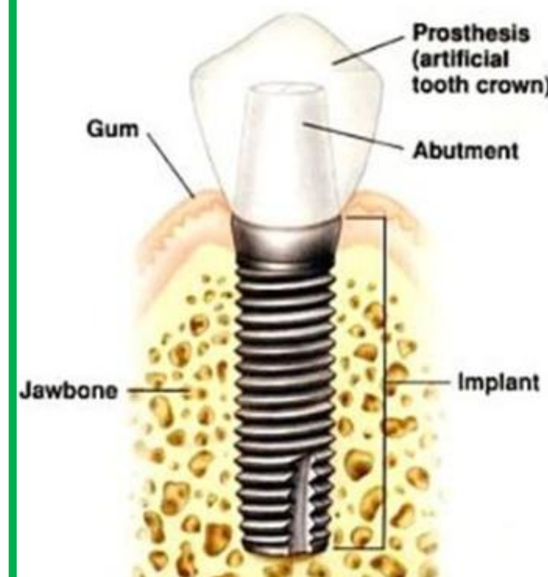
JJ Peng, ***PhD Thesis***, Wuhan University (2009)



Apparent density: 5.68 g/cm^3
(*Theoretical density:* *6.51* g/cm^3)

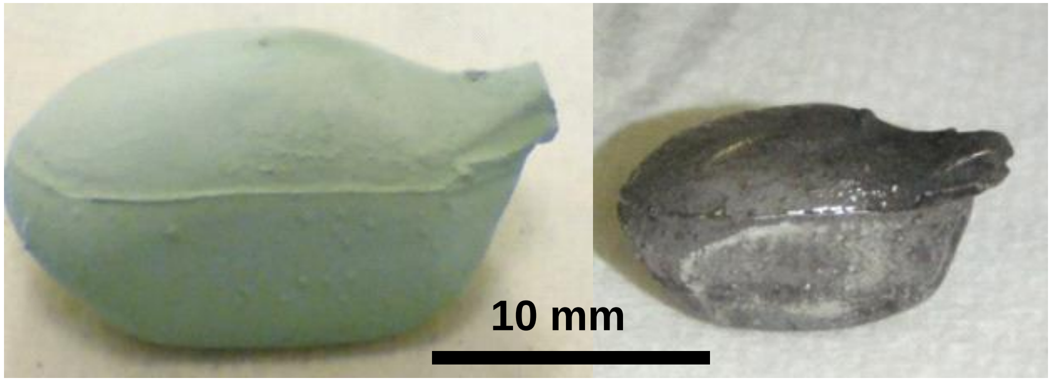
Young's modular: ca. 0.483 GPa
(*Human bone:* *7~30* GPa)

These two correlated properties are desirable for body fluid ingression and bone cell growth.



cf. Commercial Internet pages

Near-Net-Shape Products: Miniature Golf Club Head



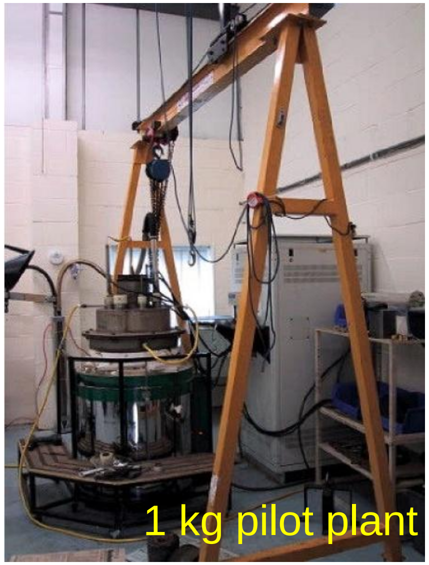
Direct electro-metallisation of a hollow oxide precursor (left) into a miniature golf-club-head of Ti-6Al-4V alloy (right).

Photo of titanium golf club head.

Cross-section of the miniature golf-club-head

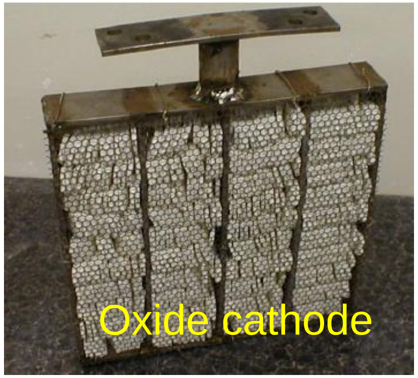
- Minor or no shape distortion
- Near-net-shape production of Ti-6Al-4V components
- Significant densification
- Solid or hollow components.

D Hu, W Xiao, GZ Chen, ***Metall. Mater. Trans. B,*** 44 (2013) 272-282



Commercialisation

Metalysis holds exclusive licence of the FFC Cambridge Process



M. Jackson, ***Materials World***, May 2007, p. 32

C. Schwandt, G.R. Doughty, D.J. Fray, ***Key Eng. Mater.,*** 436 (2010) 13.

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Past and present co-workers whose names appear in the references cited in this presentation

Thank you for your attention!
Your questions, please!