Green Microfactories: Products from Waste

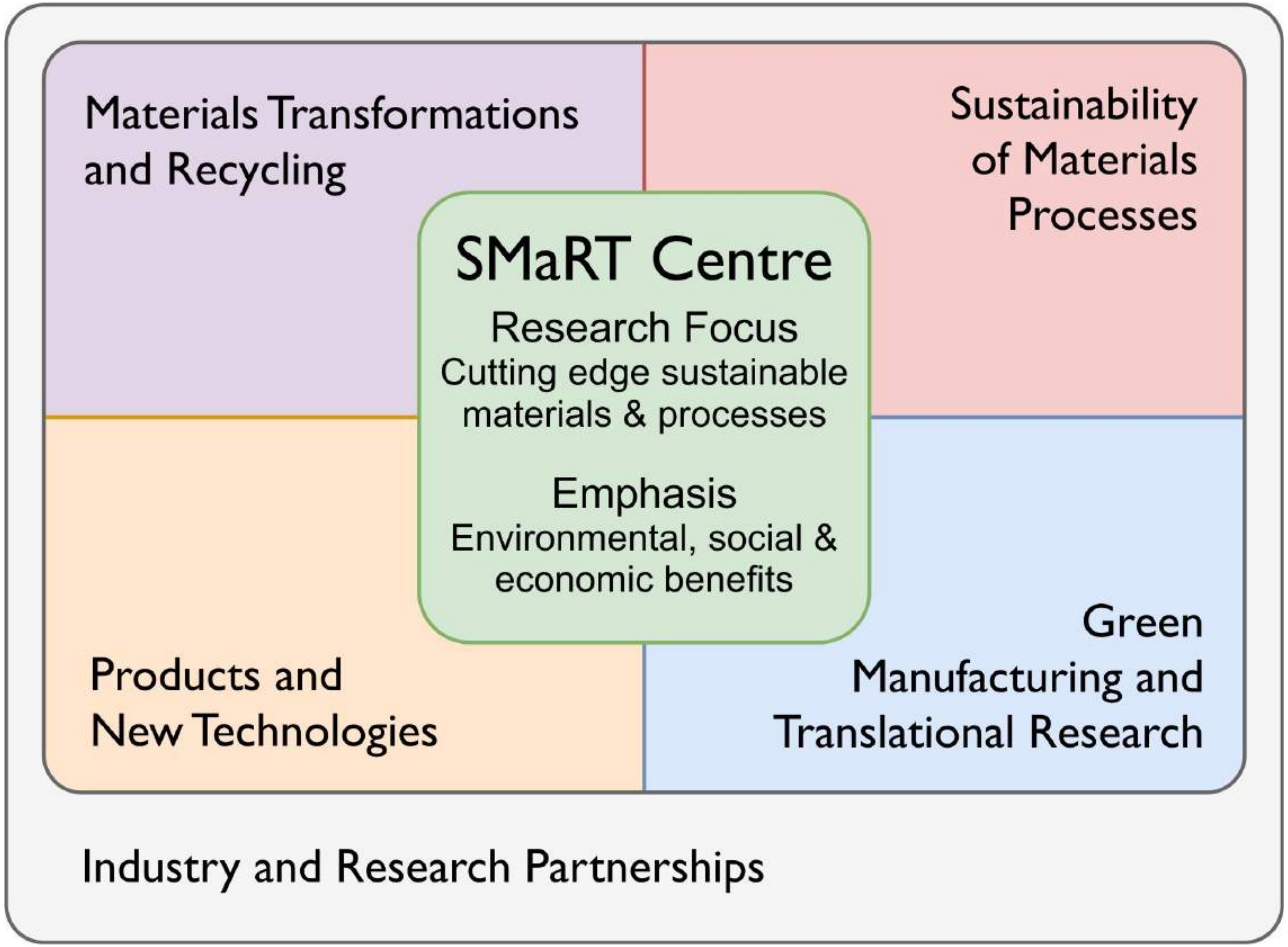
Professor Veena Sahajwalla

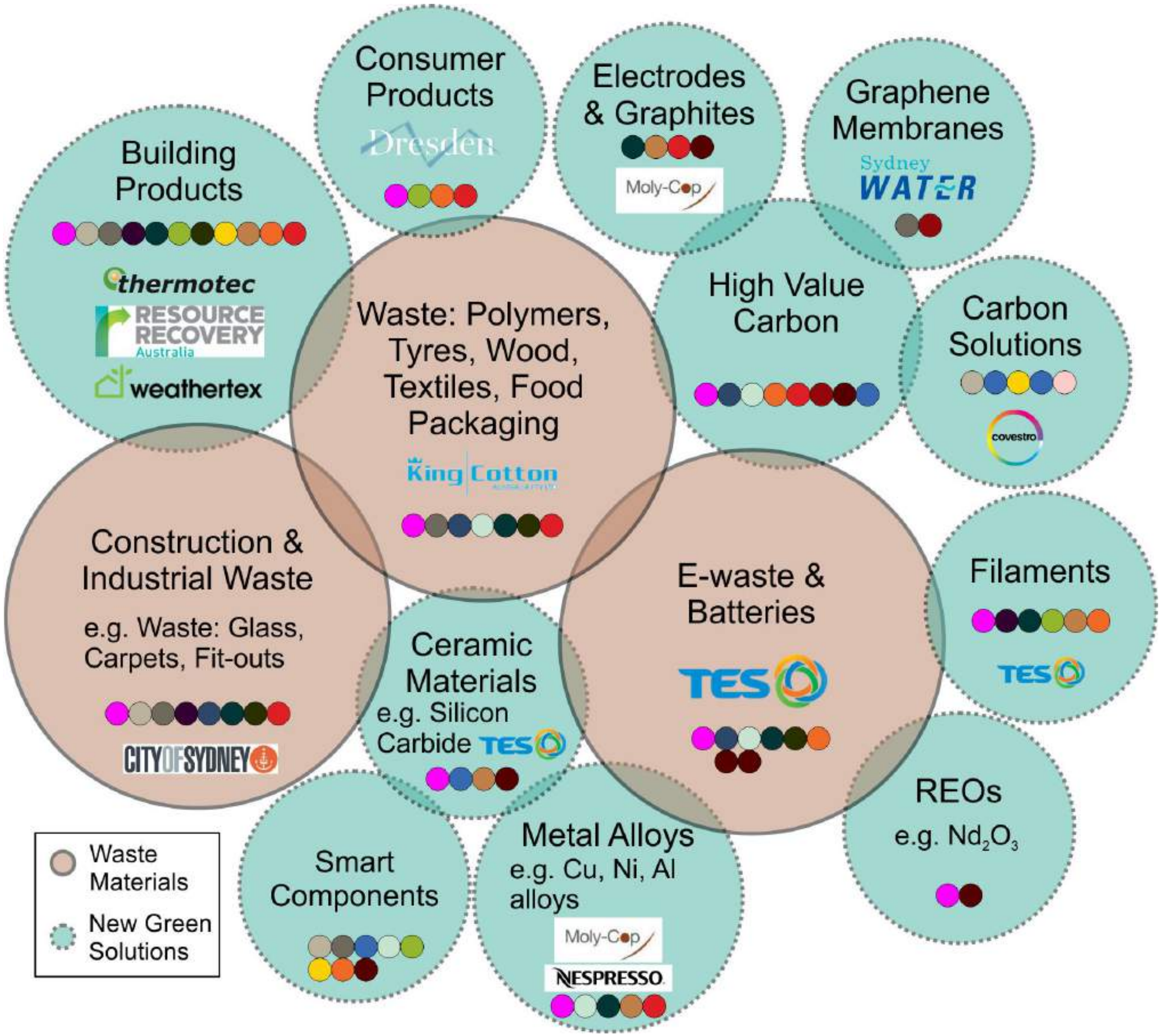
ARC Laureate Fellow

Director, ARC Research Hub:

Transforming waste directly in cost-effective green manufacturing

SMaRT@UNSW
Sustainable Materials Research & Technology


Materials Transformations and Recycling
Sustainability of Materials Processes
SMaRT Centre
Research Focus
Cutting edge sustainable materials & processes
Emphasis
Environmental, social & economic benefits
Products and New Technologies
Green Manufacturing and Translational Research
Industry and Research Partnerships


Consumer Products
Dresden
Electrodes & Graphites
Moly-Cop
Graphene Membranes
Sydney WATER
Building Products
thermotec
RESOURCE RECOVERY Australia
weathertex
Waste: Polymers, Tyres, Wood, Textiles, Food Packaging
King Cotton
High Value Carbon
Carbon Solutions
covestro
Construction & Industrial Waste
e.g. Waste: Glass, Carpets, Fit-outs
CITY OF SYDNEY
Ceramic Materials
e.g. Silicon Carbide TES
E-waste & Batteries
TES
Filaments
TES
REOs
e.g. Nd_2O_3
Smart Components
Metal Alloys
e.g. Cu, Ni, Al alloys
Moly-Cop
NESPRESSO
Waste Materials
New Green Solutions

- The traditional 3 R’s – Reduce, Reuse, Recycle – cannot cope with the complexity and volume of waste generated
- Need to reimagine and innovate in our approach to waste management
- Waste to value

Electronic Waste (E-Waste)

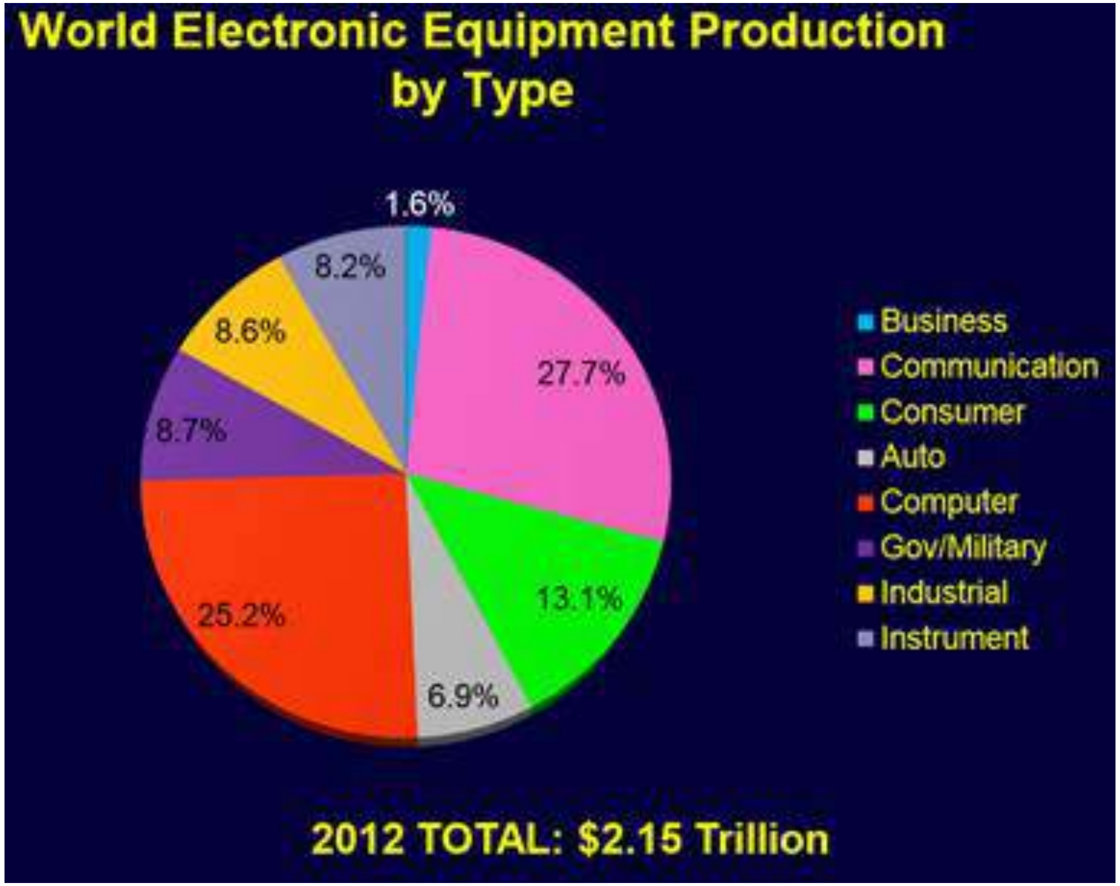
- Electronic waste covers a wide range of end-of-life electric and electronic equipment considered obsolete by their users
- Increasing from 3% to 5% every year.
- 400-700 million computers will be generated in developing countries by 2030
- According to the EPA, electronic waste is growing 2-3 times faster than any other waste

Each year around 50 million tones of e-waste are produced

E-waste

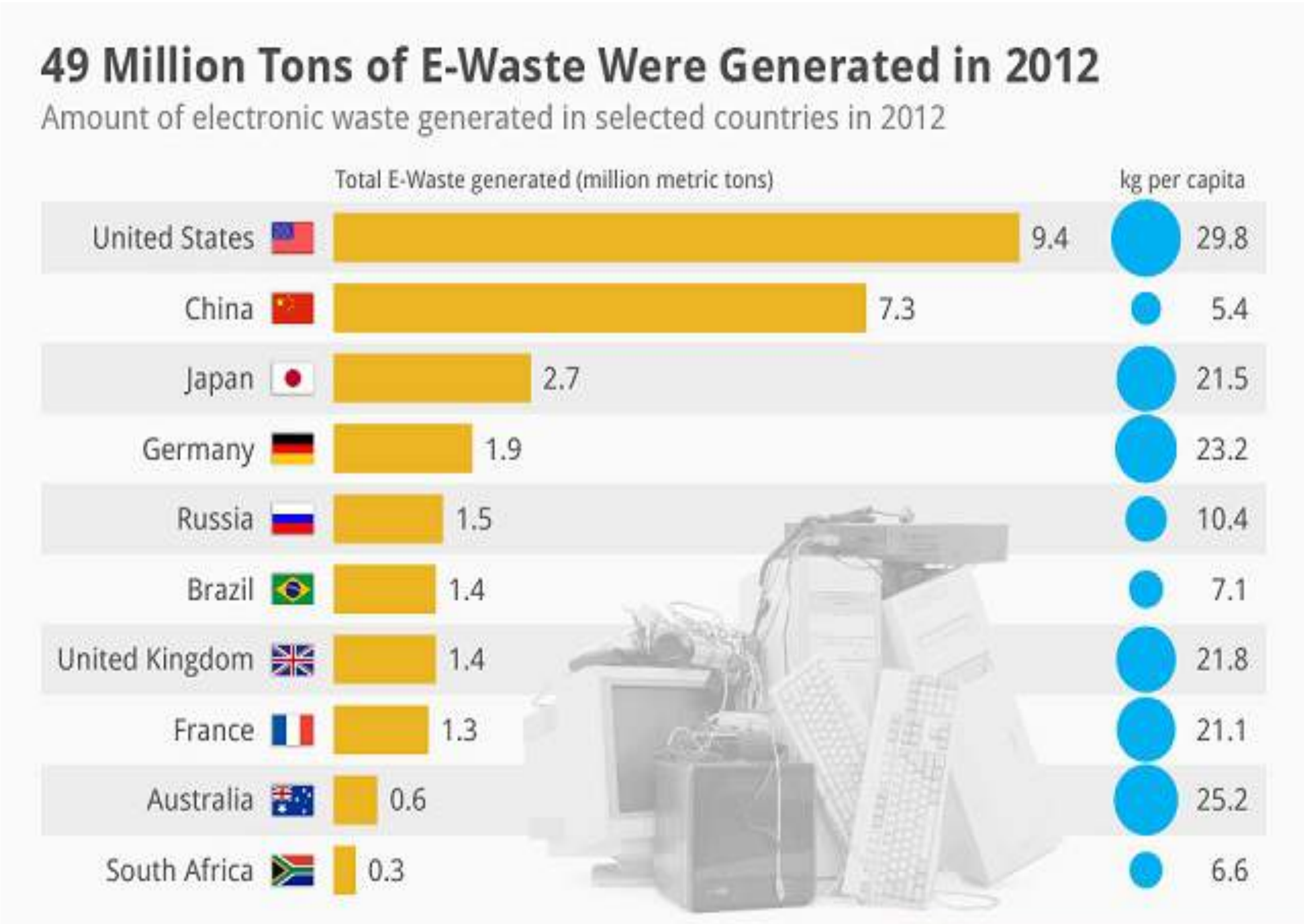
Electronic Waste

In 2012 world electronic equipment production was $2.15 trillion[1] and 25% of that is related to computer production and more than 27% is communication equipment.



Ref: https://www.ttieurope.com/docs/IO/29785/20130929.pdf

Growth of E-waste



The E-waste Challenge & Opportunity

Worldwide, the UN Environment Program estimates **42 million tonnes** of electronic waste was generated in 2014, increasing from 3% to 5% every year.

This e-waste contained nearly **$70 billion** worth of embedded resources.

In Australia, **4 million computers** are expected to be sold every year and **less than 1.5 %** will be recycled

PCBs typically contain 40 wt% metals, 30 wt% organics and 30 wt% ceramics

Problems with Incineration / Field Burning

- Release of Dioxins and Furans to the atmosphere.
- Loss of pure metals due to oxidation process.
- Loss of valuable carbon during burning process

Environmental concerns

The world production of ELVs was estimated at around 40 million units each year. Only in USA, over 12 million vehicles reach end of life each year.

Around 75-80% of shredded materials, mainly ferrous and non-ferrous fractions, are further processed and recycled, while the remaining light non-metals fraction, for which recycling processes are not in place yet, is disposed of.

Although there is insufficient data about the global production of ASR, in 2002, it has predicted at around 10 million tonnes.

Composition of ASR

Table 1
Composition of ASR.

Proximate analysis		Ultimate analysis					
Polypropylene	30–39%	C (%)	7.3–13.8	Br (%)	1.5–2.4	I (ppm)	52.9
Polyethylene	21–28%	Ti (%)	1.8–3.2	Cl (%)	0.19–0.23	K (ppm)	826
Polyurethane	9–14%	Ca (%)	0.8–1.1	N (%)	0.3–0.38	Mn (ppm)	18.4
Polycarbonate	7–12%	Si (%)	0.5–0.9	Ba (ppm)	102.7	Na (ppm)	325.1
Textiles	1–2%	Mg (%)	0.2–0.3	Cr (ppm)	35.0	Ni (ppm)	12.6
Moisture	0.8–1.1%	S (%)	0.3–0.4	Cu (ppm)	27.2	P (ppm)	583
Ash	2–3.9%	Al (%)	0.1–0.12	Fe (ppm)	88.7	Pb (ppm)	45.5
Others	4–8%	Sb (%)	1.5–2.3	Hg (ppm)	14.7	Sn (ppm)	361

Ref: ACS Sustainable Chemistry & Engineering, 5, 5440 – 5448.
doi: 10.1021/acssuschemeng.7b00774
"Green Hub" IH130200025

E-waste Plastics

- Transform varied waste plastics into value added products
- Enable rapid characterisation and sorting of plastics
- The technology should be economically and environmentally sustainable
- It should readily integrate with industry
- The resultant value added products should be commercially relevant and have access to new and existing market

Conversion of Waste Plastics into 3D Printed Products

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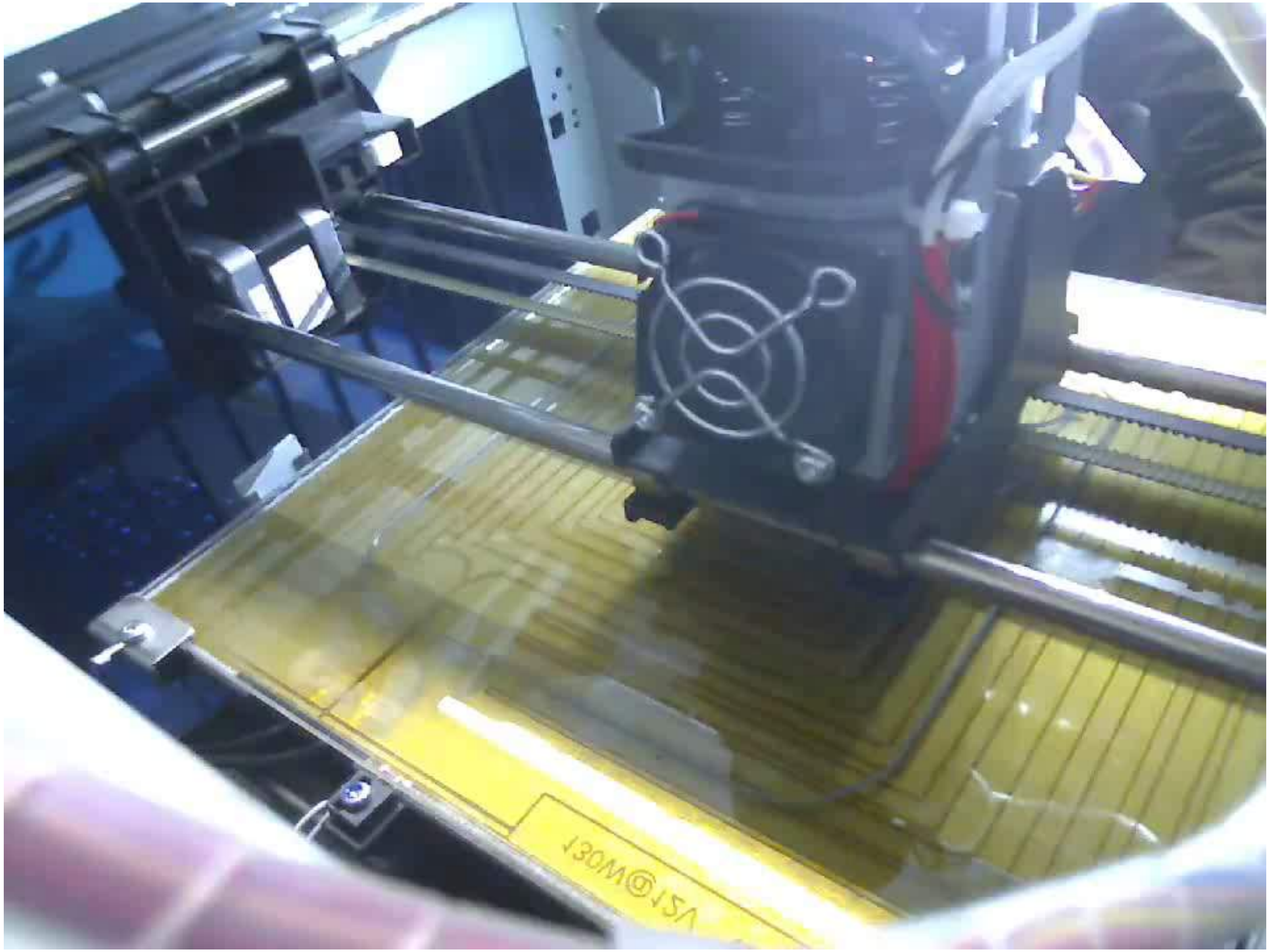
3D Printing 100% Recycled Filament



Percentage of Metals and Non-metals in PCBs

PCBs present a diverse and complex mixture of elements consisting:

- ~ 43% polymers
- ~ 34% refractories
- ~ 23% metals

(Christian Hagelüken and Christopher W Corti., 2010)

Comparison of recovery of Copper from e-waste Vs ores

Copper in PCB range from 10% to 20%

(Cui and Zhang, 2008; Schluep et al., 2009)

Copper in ores range from ~0.5% to 1%

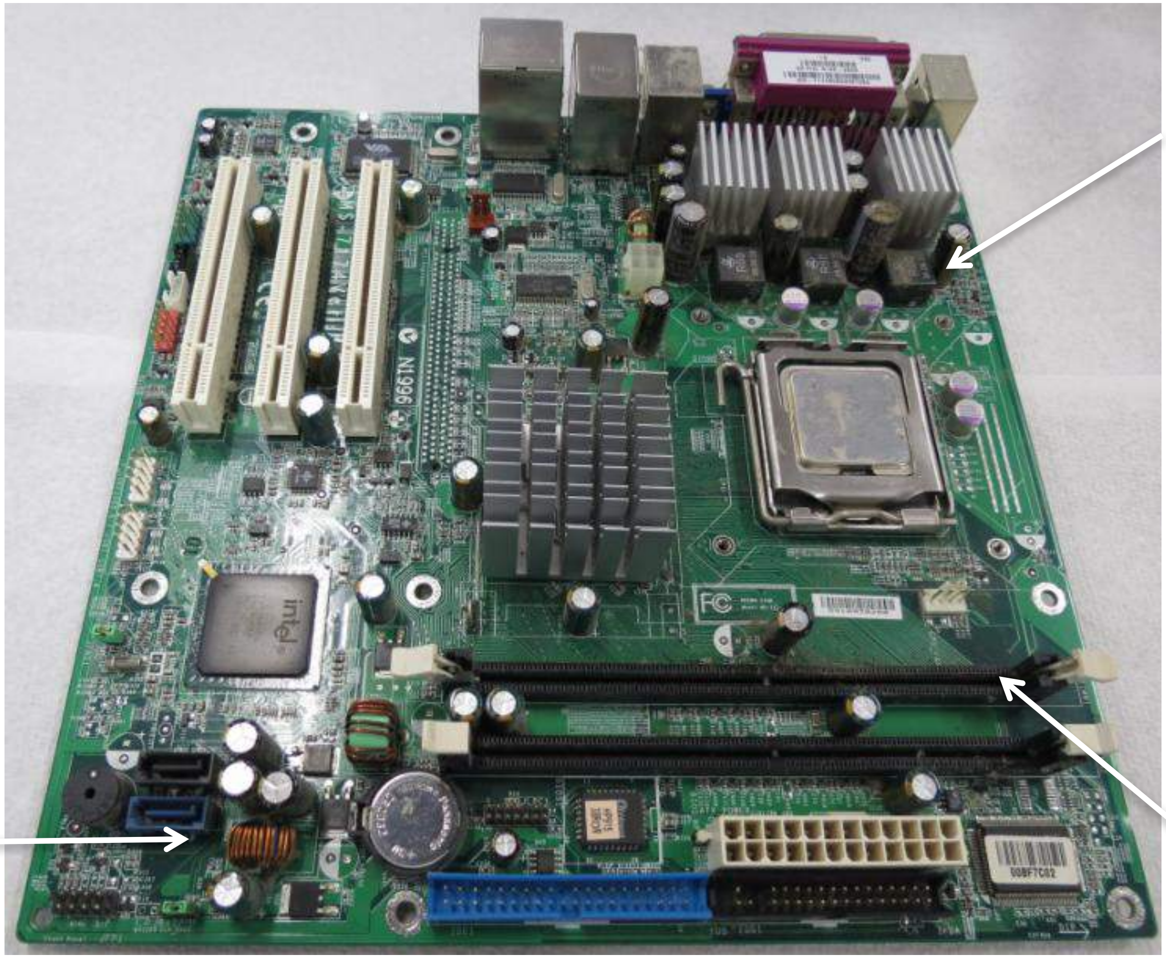
(Davenport et al., 2002), requiring a different type of processing to recover metal.

Printed Circuit Board

30% ceramics

30% polymers

40% metals



Silver

Gold

Palladium

Cu 10-20%

Carbon

Sources: Schluep, M, Hagelueken, C, Magalini, R, Maurer, C, Meskers, C, Mueller, E & Wang, F 2009, *Recycling - From E-Waste to Resources*.
Cui, J & Zhang, L 2008, 'Metallurgical recovery of metals from electronic waste: A review', *Journal of Hazardous Materials*, vol. 158, no. 2–3, pp. 228-56



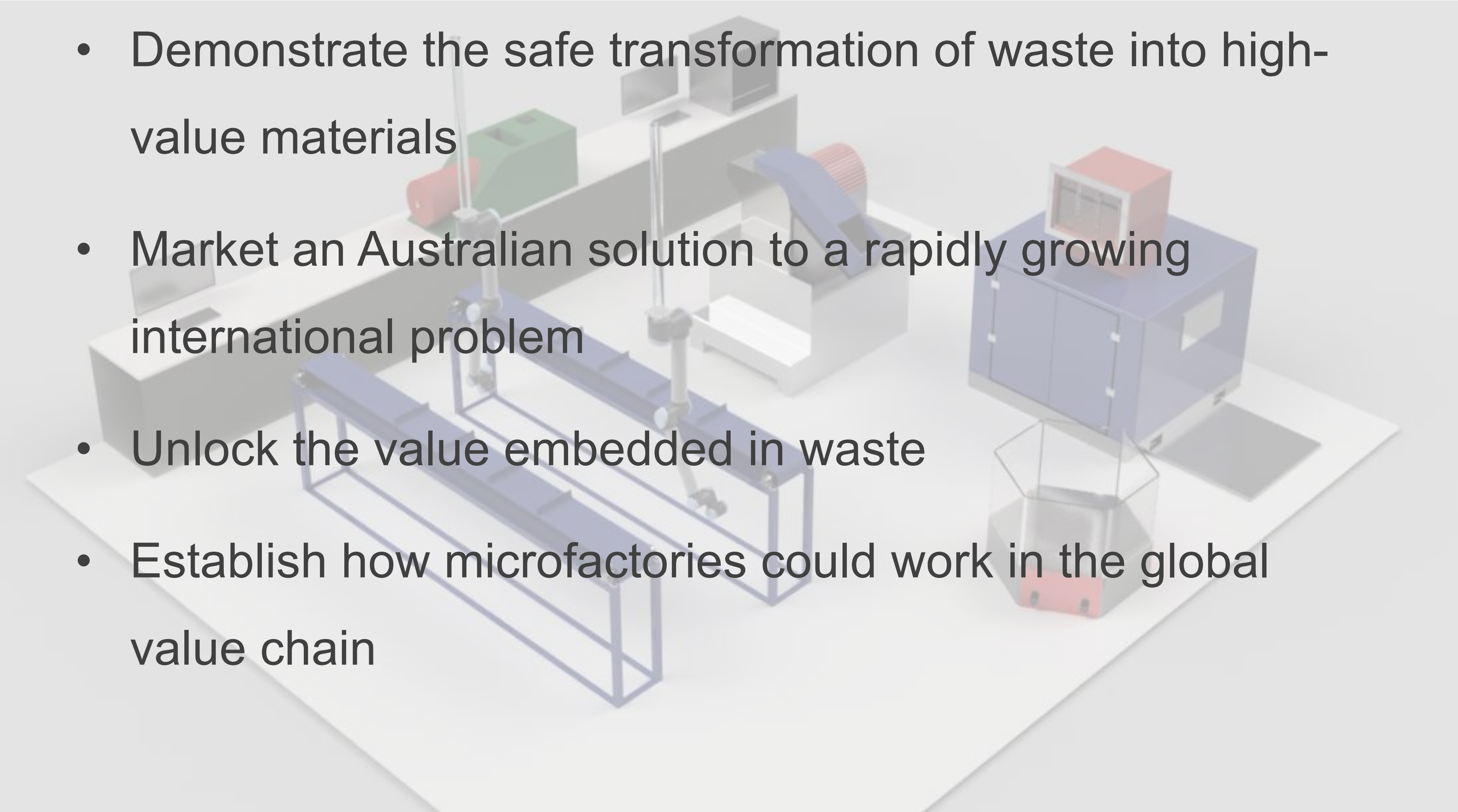


	PCB 1 **PC - Motherboard** **Ceramic Rich** **(Very Hard)**	**PCB 2** **PC-Motherboard** **Ceramic Rich** **(Hard)**	**PCB 3** **Printer Motherboard** **Polymer Rich** **(Soft)**	**PCB 4** **Old PC Motherboard** **Paper Rich** **(Soft)**	**PCB 5** **DVD Plyer** **Motherboard** **Polymer Rich** **(Very Hard)**
Cu	✓	✓	✓	✓	✓
Sn	✓		✓	✓	✓
Pb			✓	✓	
Al	✓	✓		✓	✓
Si	✓	✓	✓	✓	✓
Potential Alloys	Al-Si Cu-Sn	Cu Al-Si	Cu-Sn Cu-Sn-Pb	Cu-Sn Cu-Sn-Pb	Cu-Sn Al-Si

The SMaRT Vision

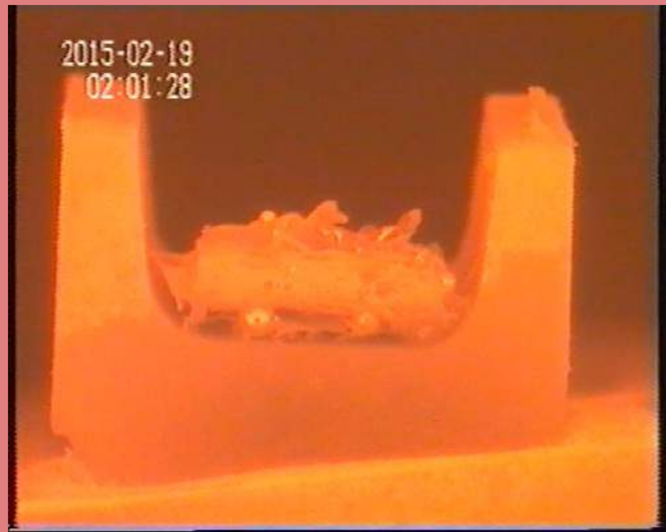
- Convert waste materials into high-value materials
- Minimise the energy-intensive transportation of waste
- Promote and support viable local economies and jobs
- An embodiment of distributed manufacturing

Microfactory: A SMaRT Solution



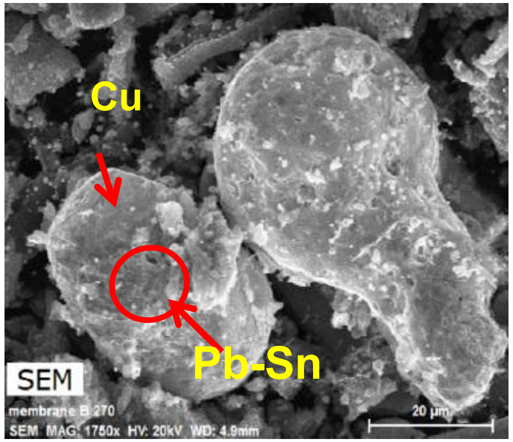
- Demonstrate the safe transformation of waste into high-value materials
- Market an Australian solution to a rapidly growing international problem
- Unlock the value embedded in waste
- Establish how microfactories could work in the global value chain

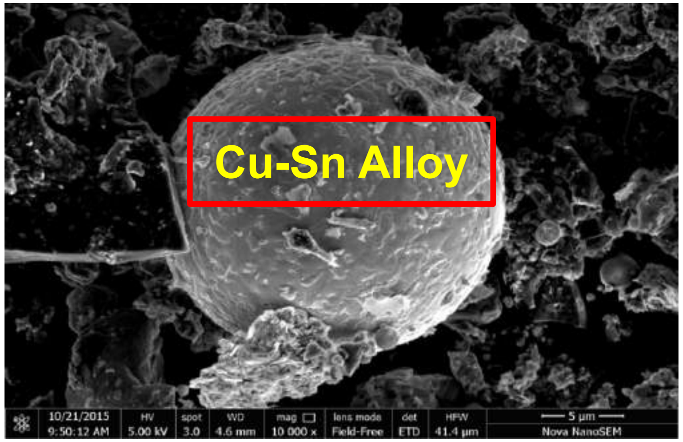
Generation of Copper Rich Metallic Phases

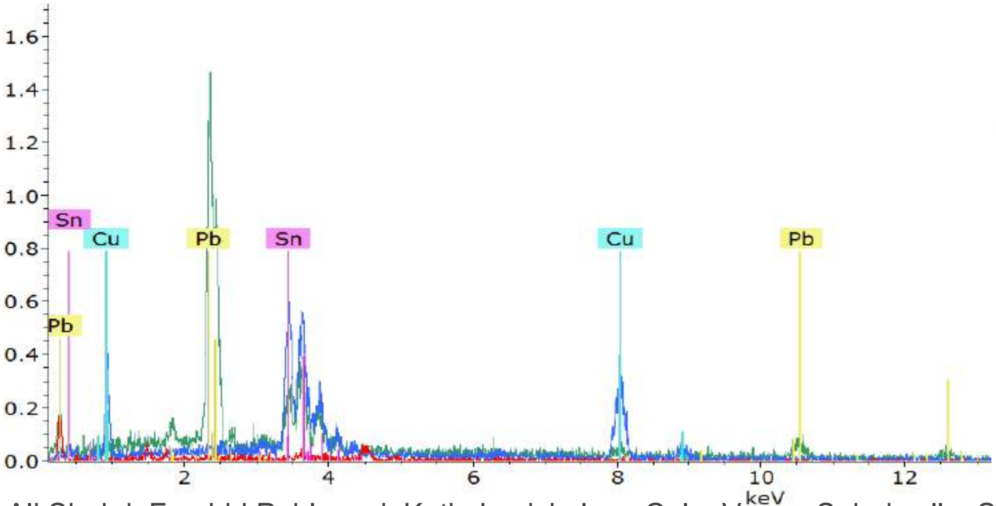


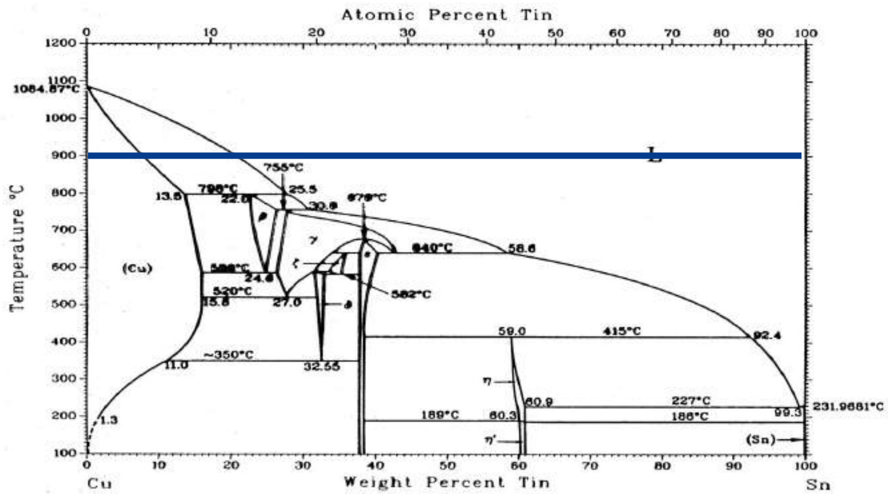
R. Cayumil, R. Khanna, M. Ikram-Ul-Haq, R. Rajarao, A. Hill, and V. Sahajwalla, "Generation of copper rich metallic phases from waste printed circuit boards," *Waste Manag.*, vol. 34, no. 10, pp. 1783–1792, 2014.

PCB 4 – 900°C – (Powder)



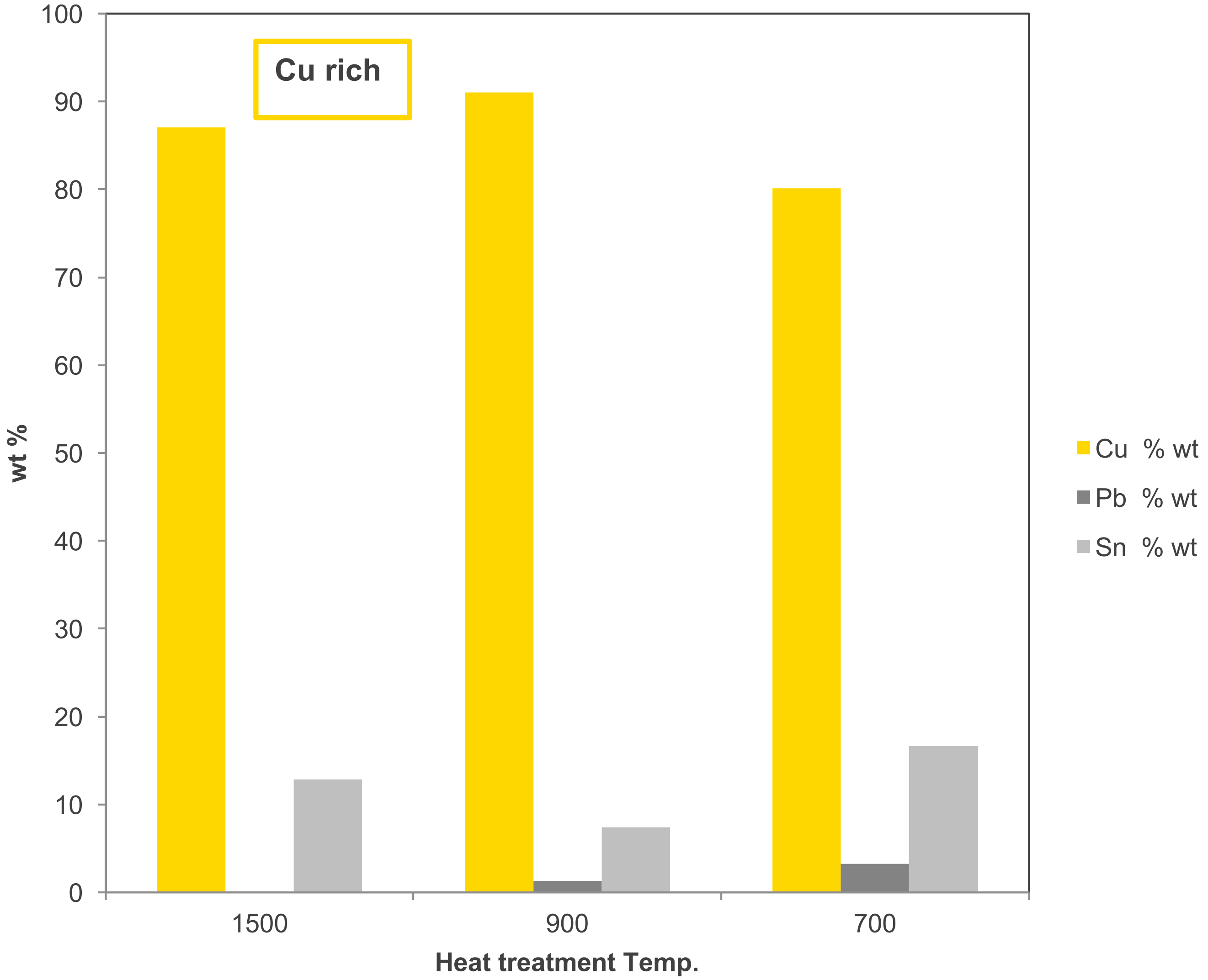




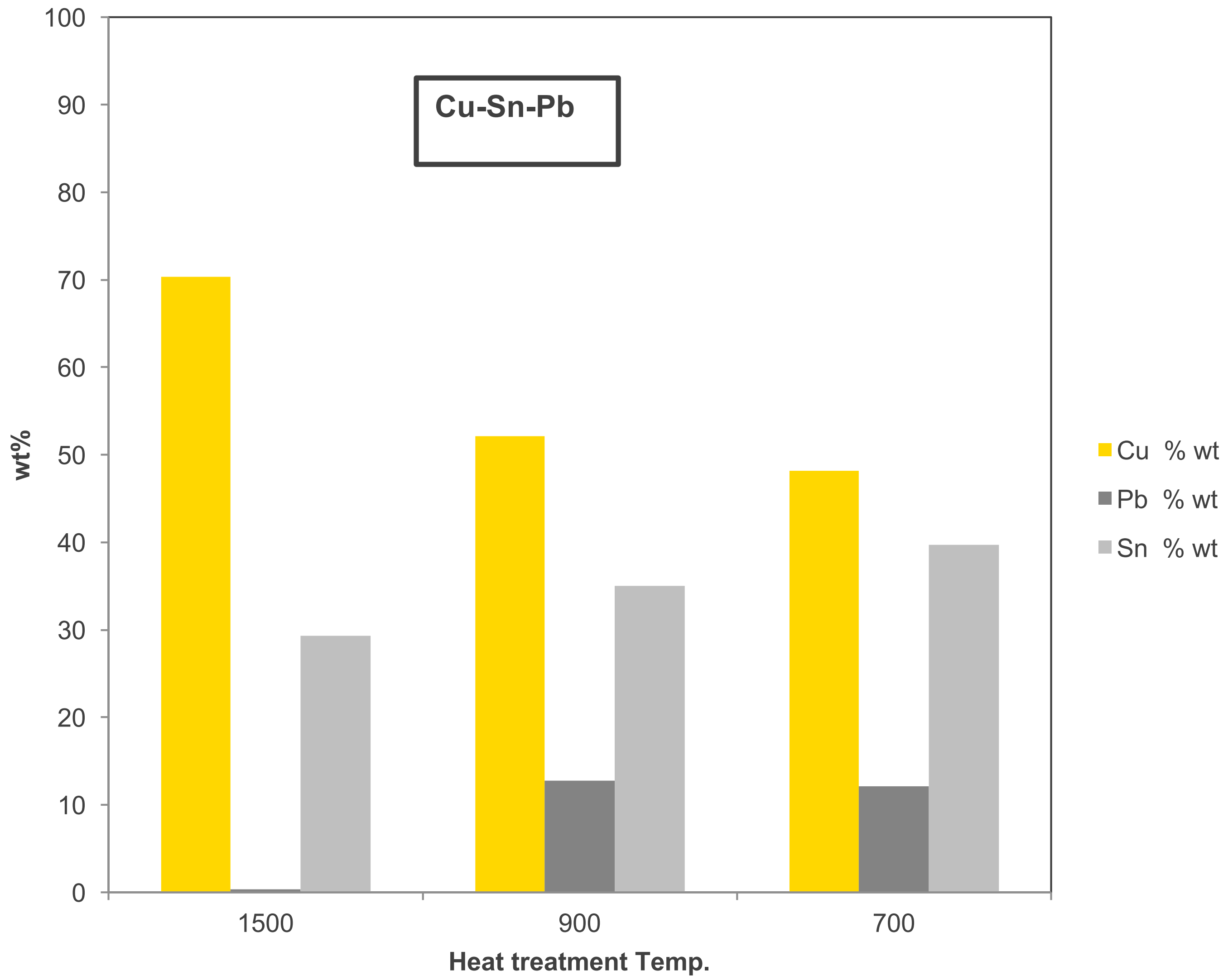


Ali Shokri, Farshid Pahlevani, Katie Levick, Ivan Cole, Veena Sahajwalla, Synthesis of copper-tin nanoparticles from old computer printed circuit boards, In Journal of Cleaner Production, Volume 142, Part 4, 2017, Pages 2586-2592, ISSN 0959-6526

PCB 4 – Bulk Heat Treatment



PCB 4 – Bulk Heat Treatment



Products from Waste Glass

E-waste glass as a source of Silica

- Glass fraction of e-waste is a rich alternative source of silicon for production of SiC and Si_3N_4
- Issues:
  - Low purity
  - Technically challenging
  - Economically unattractive
- Resources:
  - Computer monitors
  - Televisions
  - Devices with glass screens

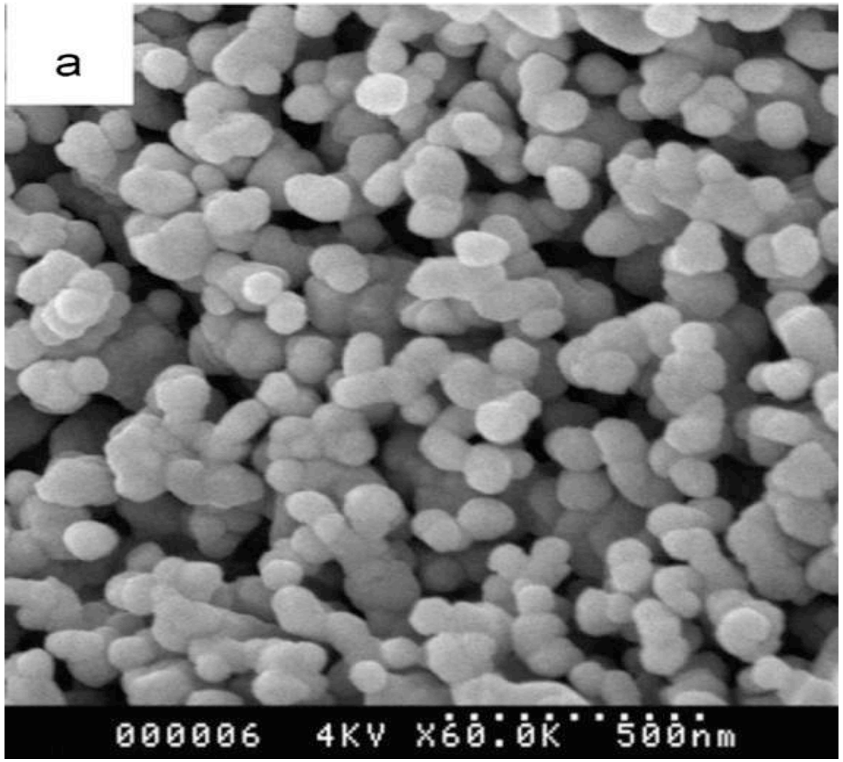
In Australia 88% of 4 million computers and 3 million TVs purchased annually ends up in landfills

oxides	Na_2O	SiO_2	Al_2O_3	CaO	MgO	MnO	Fe_2O_3
Weight percent	13.9	70.3	1.8	7.8	4.6	0.01	0.1

Silicon Carbide Nanoparticles from Waste Compact Disks

Applications

- As a high grade refractory material,
- Special material for polishing abrasive,
- Manufacture of rubber tyres
- High temperature spray nozzle manufacture
- Substrates for ICs
- Mirror coatings for high ultraviolet environments.



Rajarao, Ravindra & Ferreira, Rodolfo & Habib Fahandej Sadi, Seyed & Khanna, Rita & Sahajwalla, Veena. (2014). Synthesis of silicon carbide nanoparticles by using electronic waste as a carbon source. Materials Letters. 120. 65–68. 10.1016/j.matlet.2014.01.018.

Thermal Isolation of Rare Earth Oxides

Recycling of Nd-Fe-B Magnets

- Wide use of rare-earth elements
- Supply and cost challenges
  - Increasing domestic demand in China
  - Gradually tightened export quotas
- Inefficiencies in REEs ore mining process

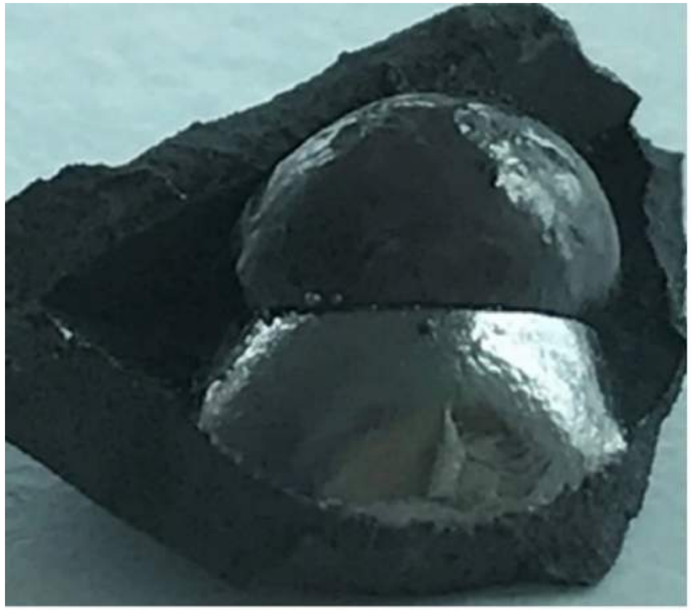
Applications:

- Computer and laptop hard drives
- Hybrid and electric vehicles
- Electric generators in turbines

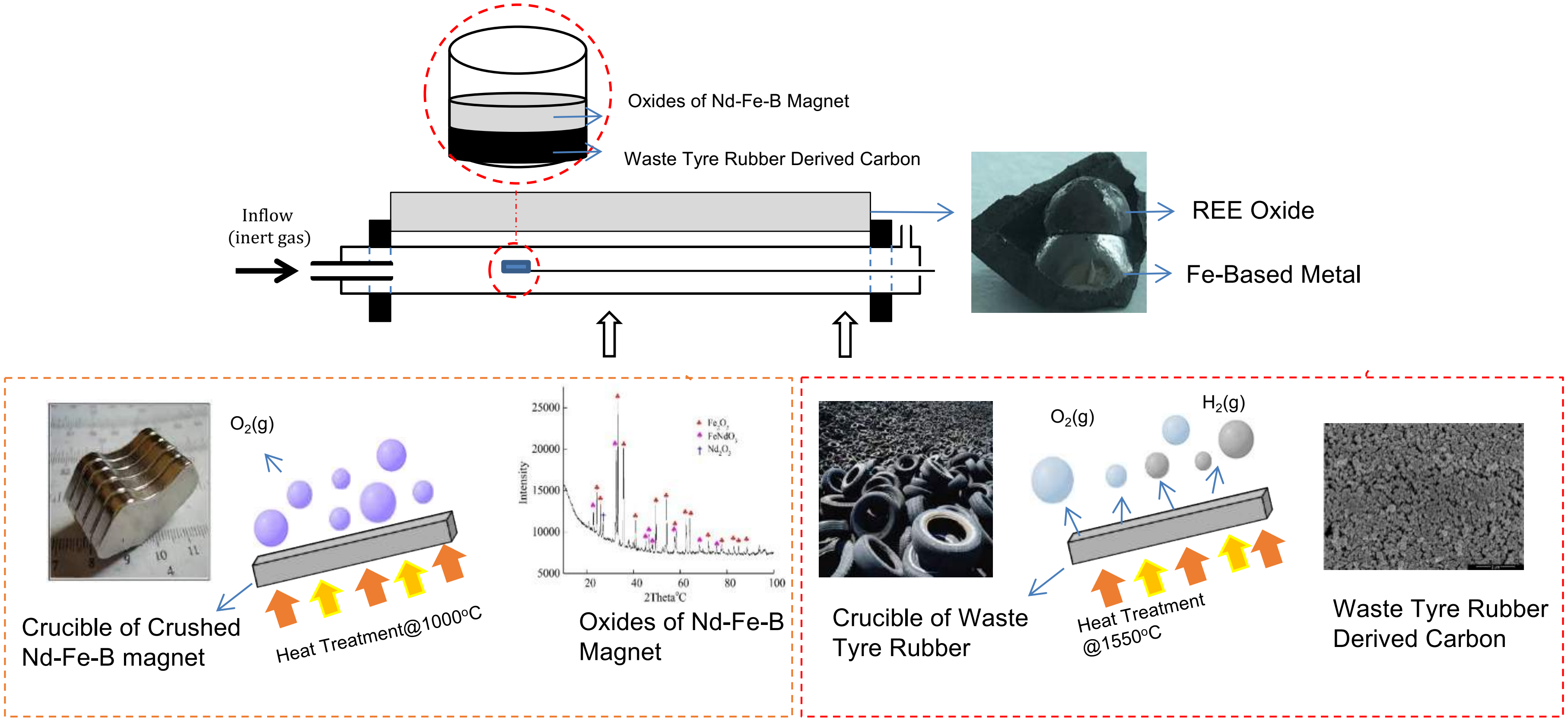
Valuable Content:
Neodymium, Dysprosium and praseodymium

Recycling:
- less than 1% of REEs are recovered

Rare-earths from a hard drive (Separated from Iron Droplets)

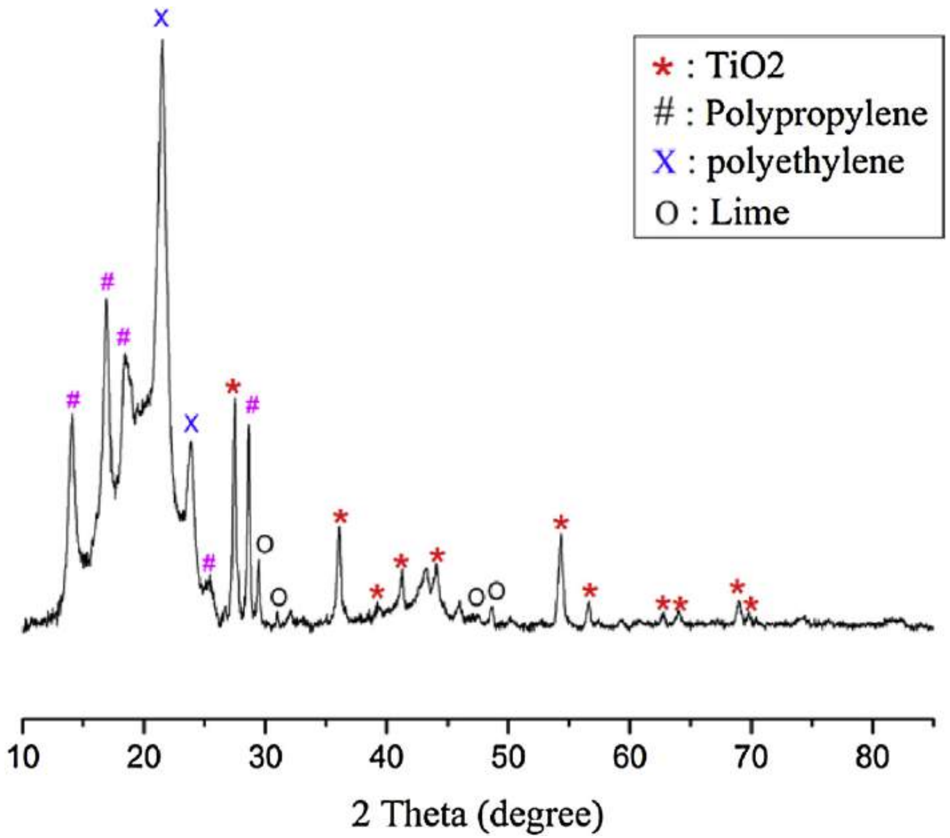


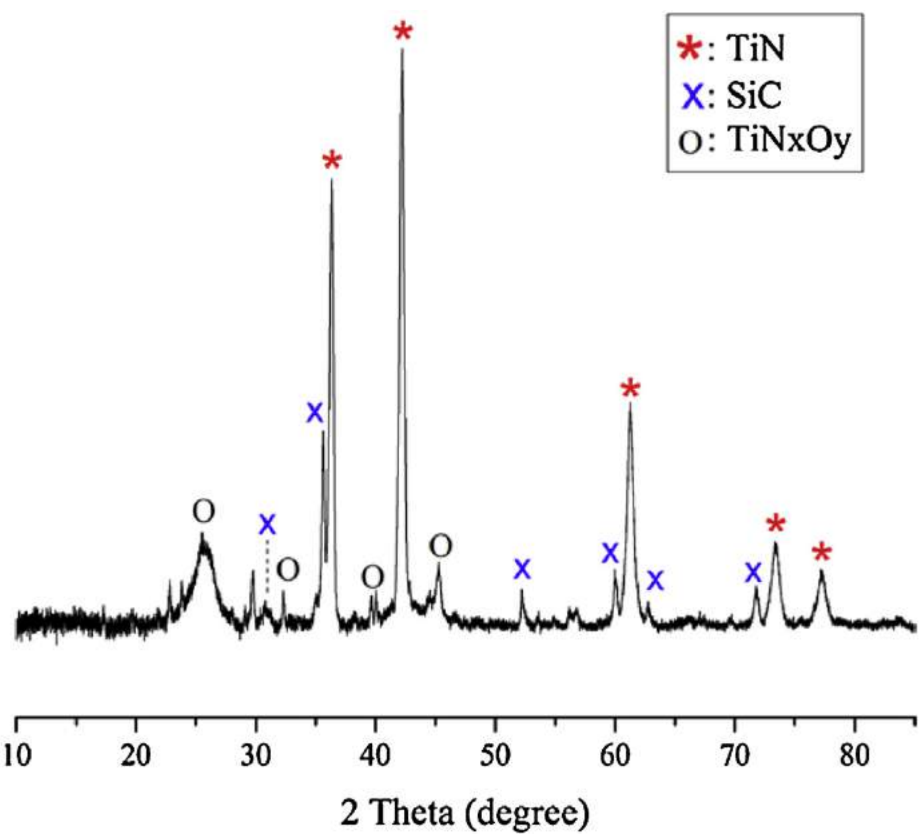
Thermal Isolation of Rare Earth Oxides



Maroufi, S.; Khayyam Nekouei, R.; Sahajwalla, V. Thermal Isolation of Rare Earth Oxides from Nd–Fe–B Magnets Using Carbon from Waste Tyres. ***ACS Sustain. Chem***. *Eng.* 2017.

XRD Pattern of ASR

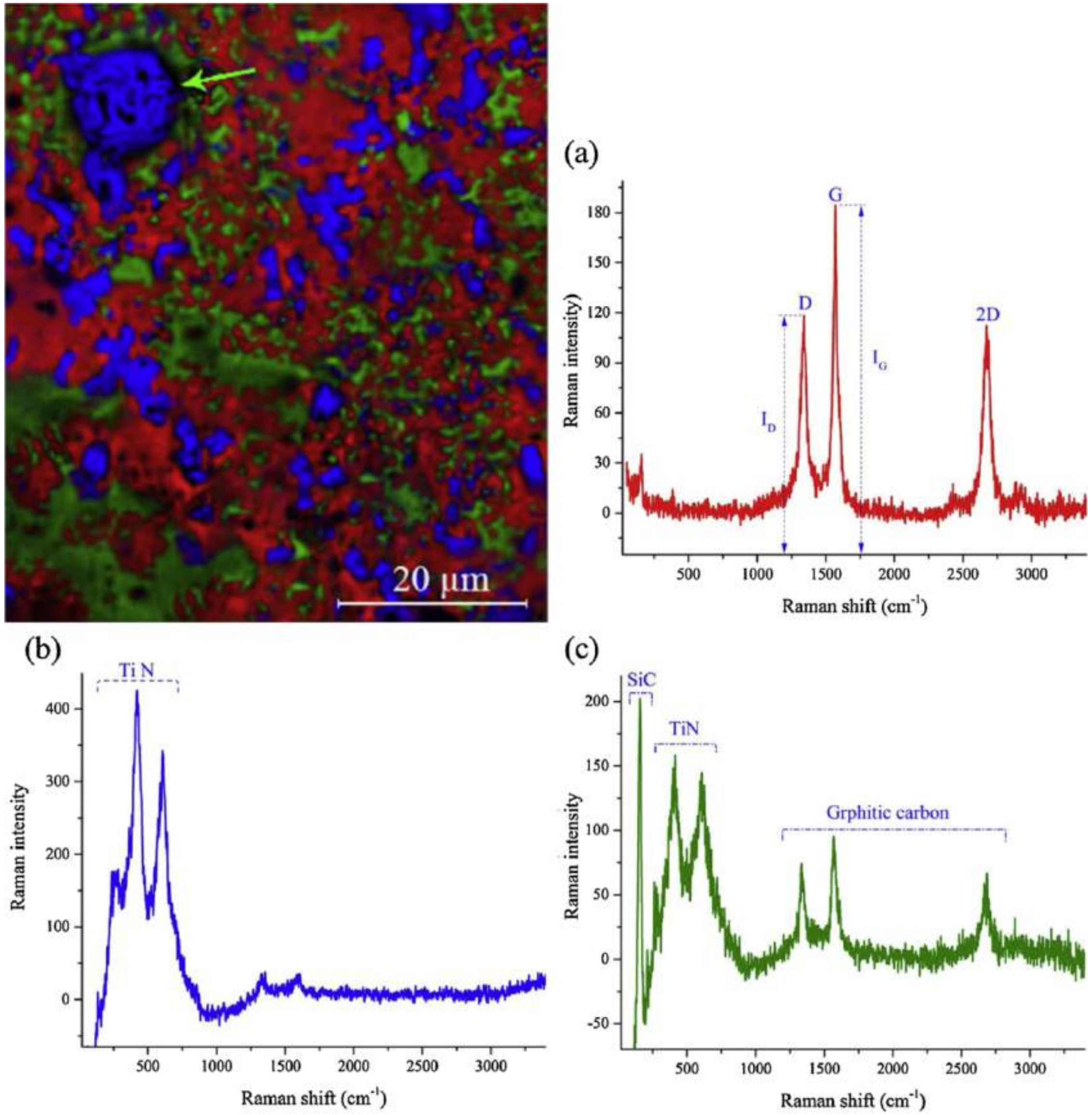




ASR

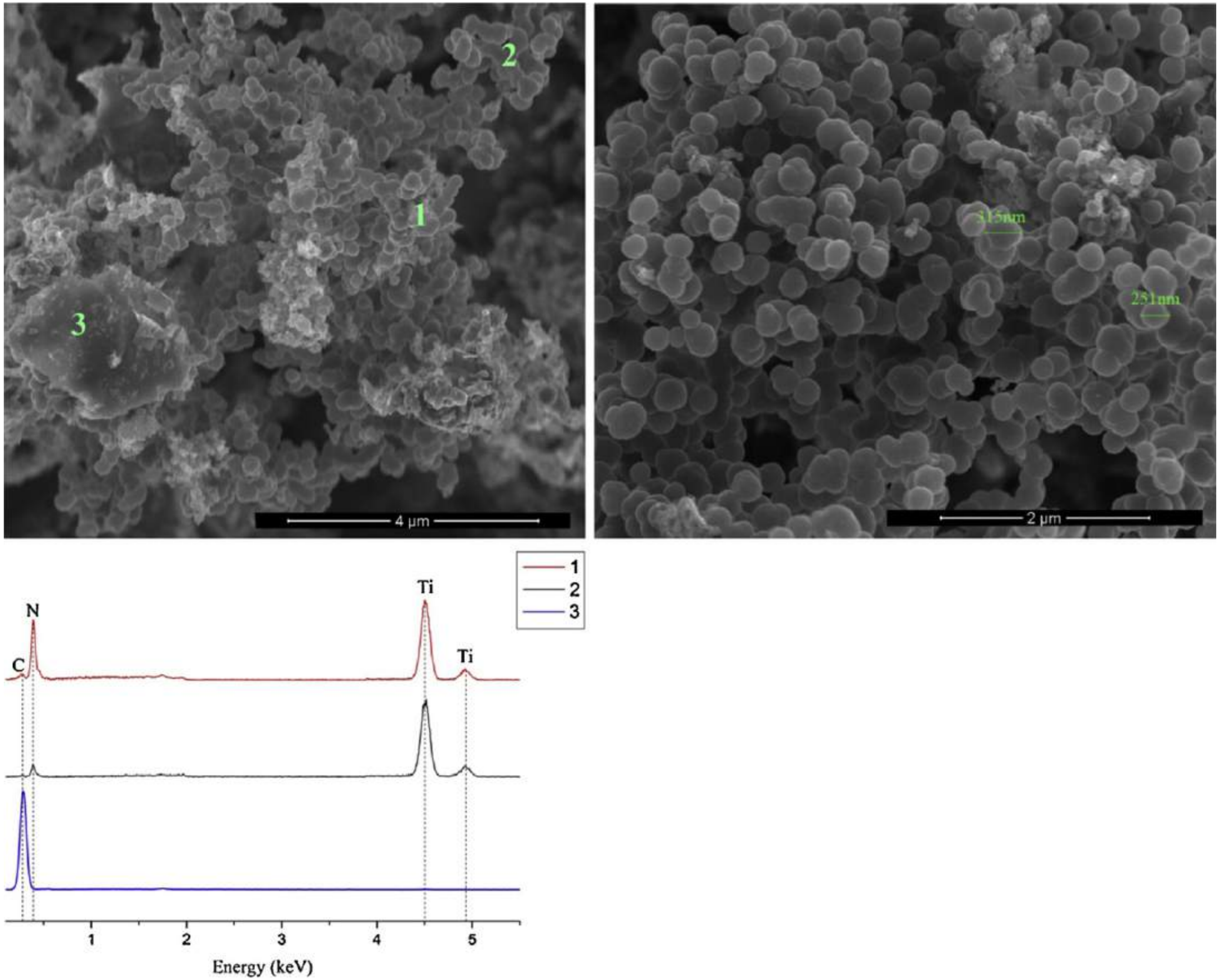
Selective Thermal Transformation

Ref: Journal of Analytical and Applied Pyrolysis, 2016, [doi:10.1016/j.jaap.2016.04.010](https://doi.org/10.1016/j.jaap.2016.04.010)
"Green Hub" IH130200025



RIM analysis of ASR-1550. (a) represents the Raman spectrum of the red region, (b) the blue region and (c) the green region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ref: Waste Management, 50, 173-183. doi:[10.1016/j.wasman.2016.02.003](https://doi.org/10.1016/j.wasman.2016.02.003)
"Green Hub" IH130200025



The morphology and elemental composition of the nanostructures in ASR-1550 at high magnification.

Ref: Materials Letters, 176, 17-20. doi:10.1016/j.matlet.2016.04.066

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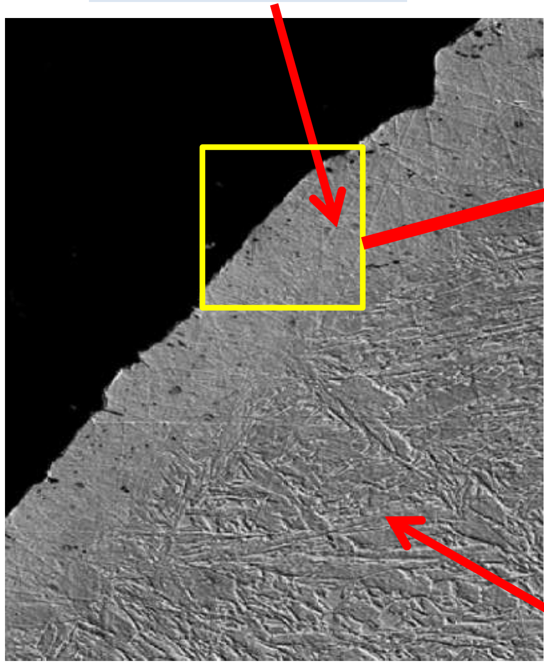
Ceramic surface in steel to achieve superior properties using ASR

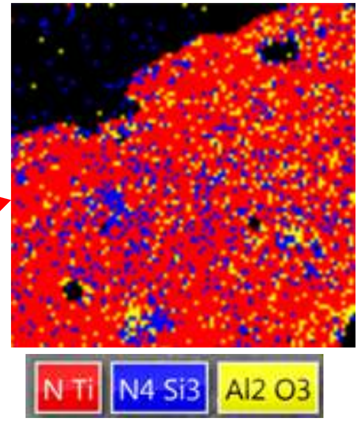
Source of ceramic component from waste

Steel component

Heat treatment

ceramic layer



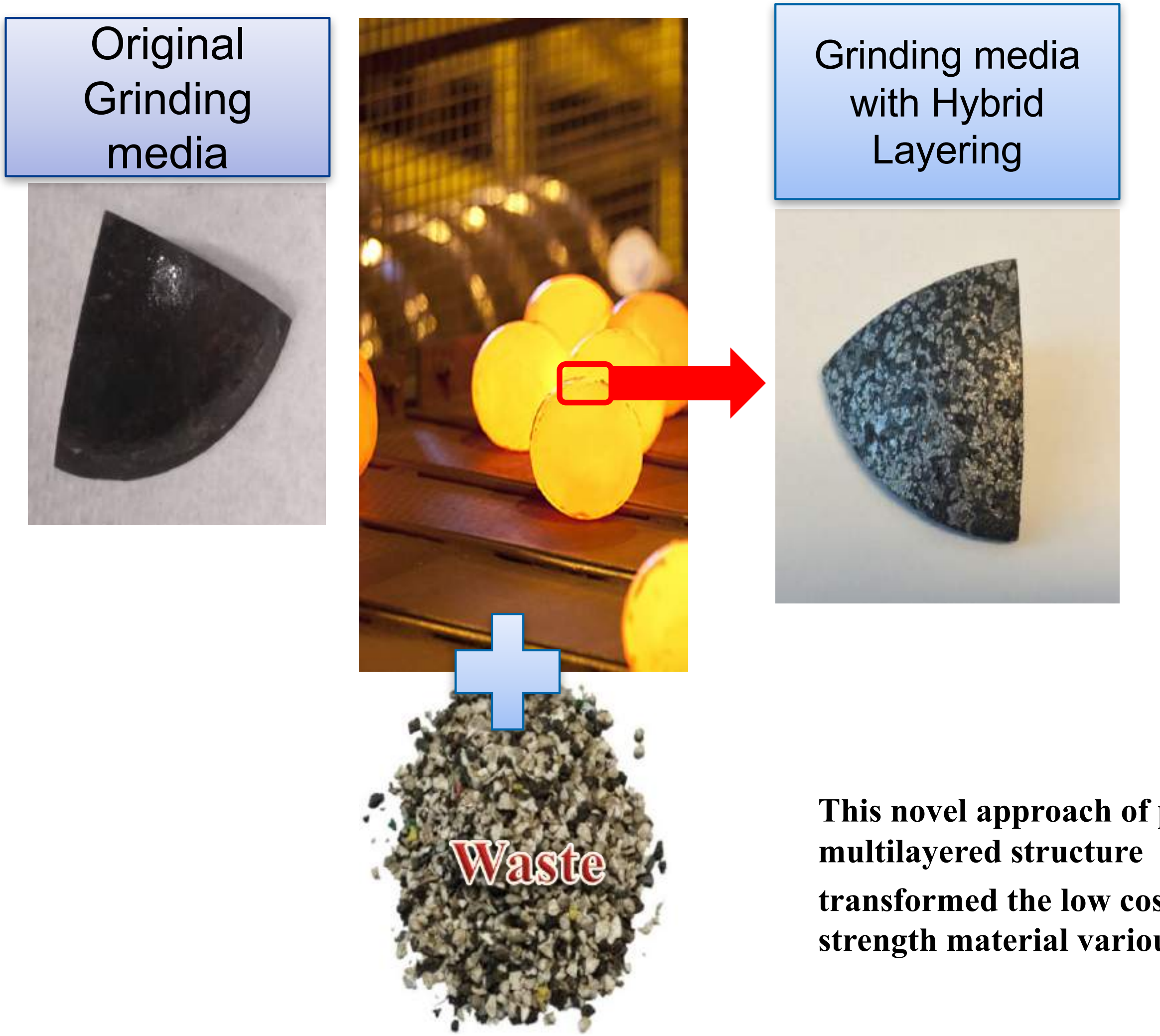


Low cost low alloyed steel

This novel approach of producing innovative ceramic structure surface transformed the low cost low alloyed steel into super strength material for various industrial applications.

Ref: Scientific Reports, 2016. **6**. 958
"Green Hub" IH130200025

Hybrid layering in steel to achieve superior properties



This novel approach of producing innovative multilayered structure

transformed the low cost low alloyed steel into super strength material various for industrial applications.

Ref: Scientific Reports, 2016. **6**. 958
"Green Hub" IH130200025

Microfactories: A Global Solution

- UNSW's microfactory technology promises to revolutionise recycling by producing cost-effective green materials.

- Relatively low entry costs for establishing recycling microfactories mean benefits can be decentralised, including the generation of jobs and economic returns in disadvantaged regions

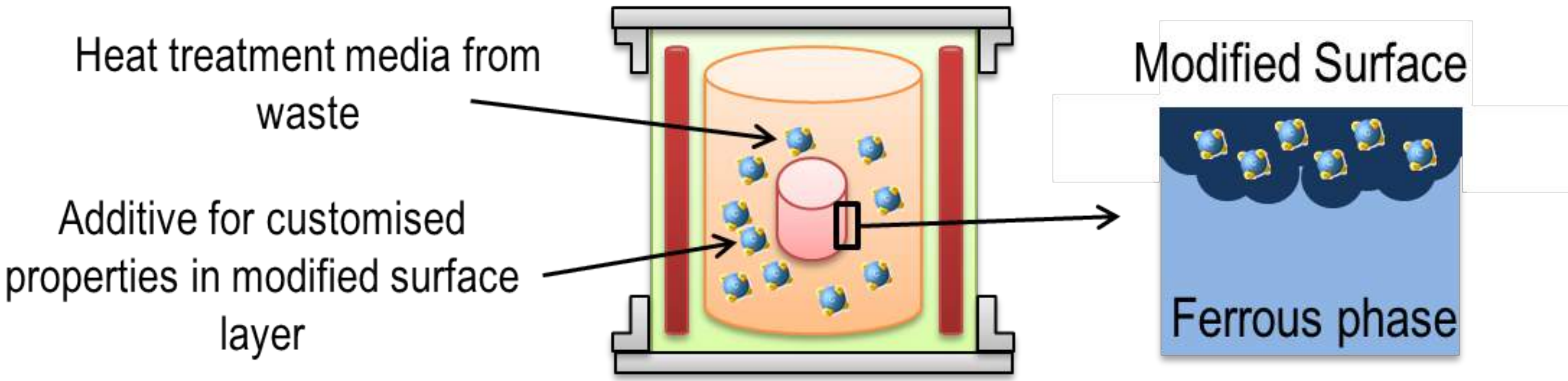
Acknowledgments

Australian Research Council through Laureate Fellowship

Grant no: FL140100215

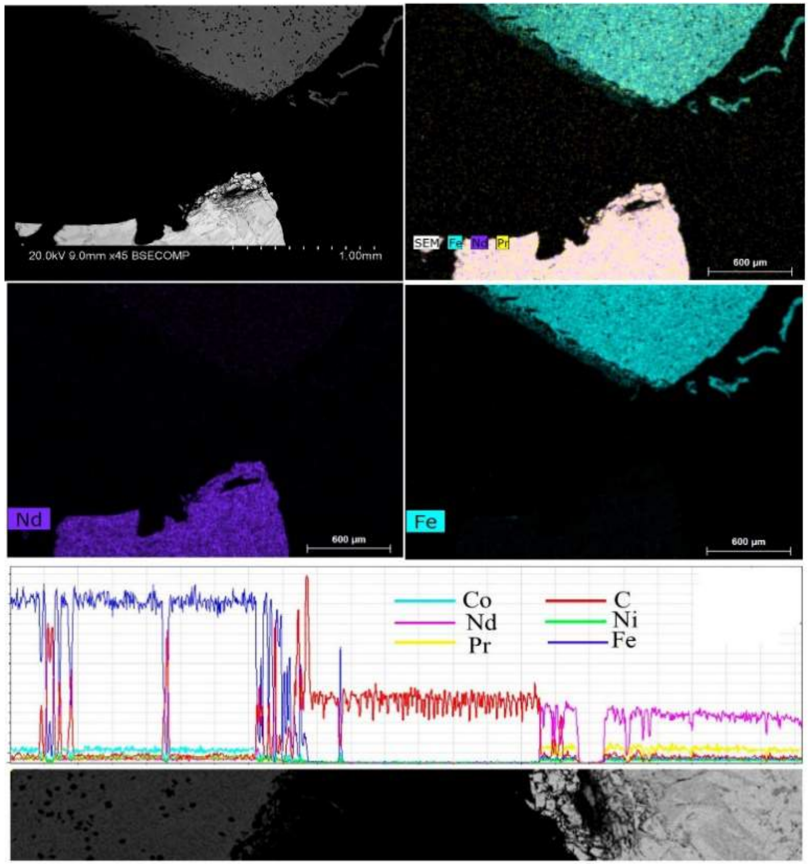
Grenew® QPQ (Quench-Polish-Quench) Surface Modification Microfactory

New low cost technique for producing a corrosion and abrasion resistant surface on normal carbon steel, using waste as a resource.

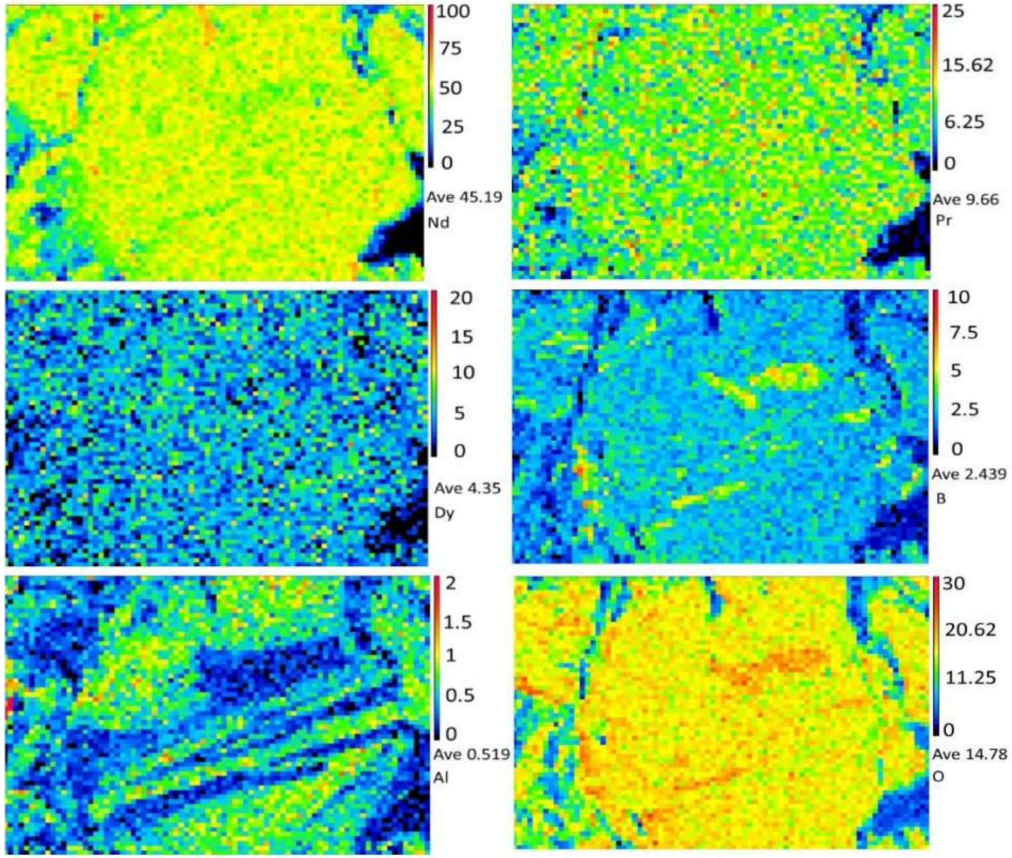


By modifying the composition of the waste input and the processing parameters, the modified surface can be effectively customised to match the intended application of the steel.

Analysis of the Oxide Phase



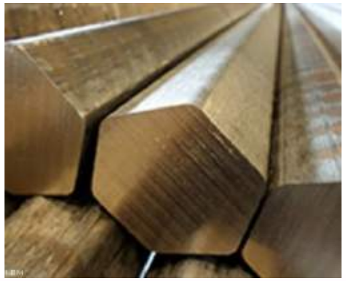
BSE image and EDS element mappings and line scan of the Fe-based metal and oxides phases separated after heat treatment at 1450°C using WTR-DC for 90 minutes



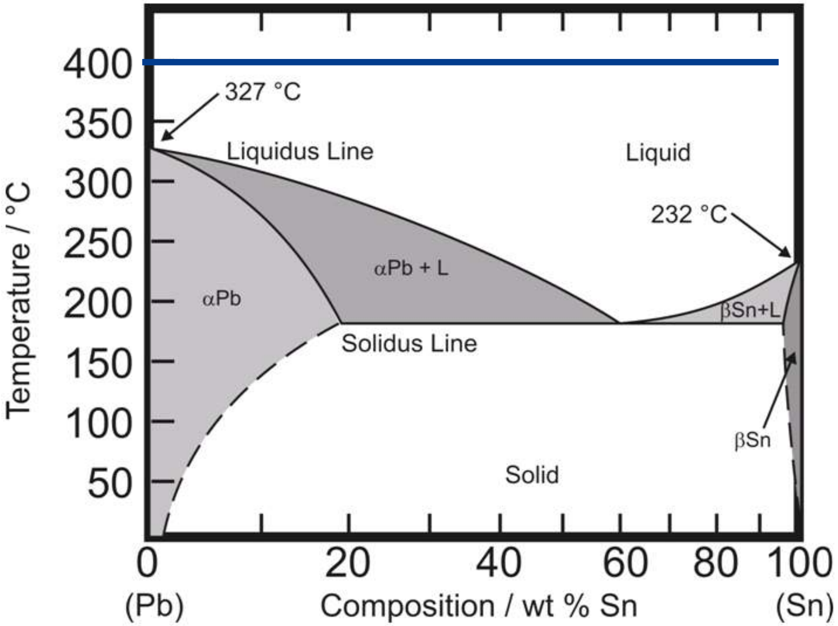
EPMA elemental mapping of the REO phase

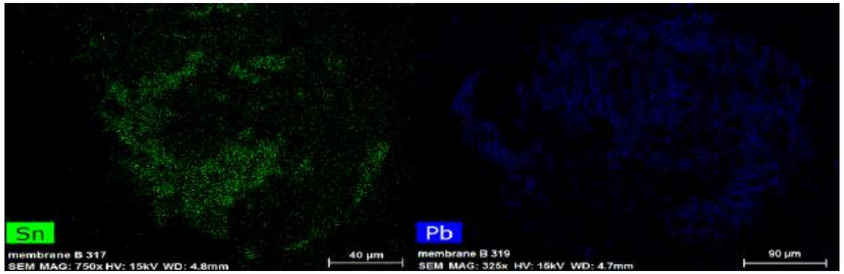
Potential commercial metallic alloy

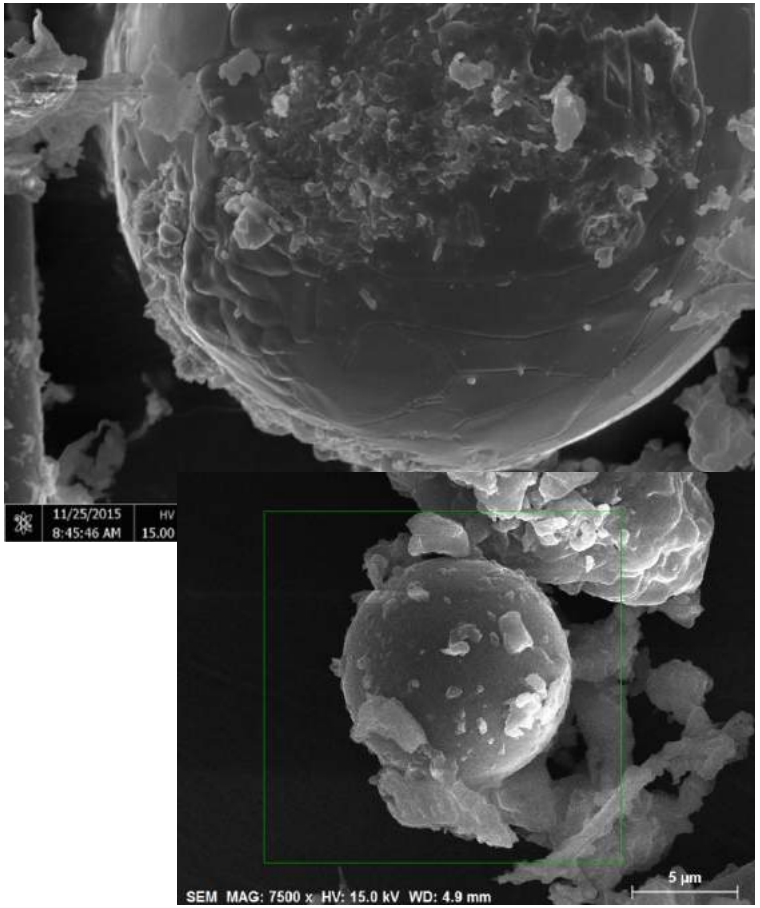
Alloy	Composition	Melting Point
	Wrought Copper alloys	
C10300 (Oxygen-freeextra-low phosphorus copper)	99.95Cu - 0.003P	1083
C15735	99.3 Cu - 0.7 Al2O3	1080
C18900	98.75 Cu - 0.75 Sn - 0.3 Si - 0.2 Mn	1075
C19000 (Copper-Nickel-Phosphorus alloy)	98.7 Cu - 1.1 Ni - 0.25 P	1085
C22000 - Commercial BronZe	90.0 Cu - 10.0 Zn	1045
C31400 - Leaded Commercial bronze	89.0 Cu - 1.75 Pb - 9.25 Zn	1040
C31600 - Leaded Commerical bronze, nickel-bearing	89.0 Cu - 1.9 Pb - 1.0 Ni - 8.1 Zn	1040
C40500	95 Cu - 1 Sn - 4 Zn	1060
C54400 - Free cutting phosphor Bronze	88.0 Cu - 4.0 Pb - 4.0 Zn - 4.0 Sn	1000
	Cast Copper alloy	
C83300 - Leaded red brasses	93 Cu - 1.5 Sn - 1.5 Pb - 4 Zn	1060
C90700 - Tin Bronze	89 Cu - 11 Sn	1000
C92500 - Leaded Tin Bronze	87 Cu - 11 Sn - 1 Pb - 1 Ni	980
C92700	88 Cu - 10 Sn - 2 Pb	980
C96200 - Copper Nickels	88.6 Cu - 10 Ni - 1.4 Fe	1150
	Tin based alloys	
Tin based bearing alloy	(Sn-Sb-Cu) small addition of Pb and Fe as impurities	400 (371)
Tin-Zinc alloy	91 Sn - 9.0 Zn	199
Tin-Lead alloy	61.86 Sn - 38.14 Pb	183



PCB 4 – 400ºC – (Powder)



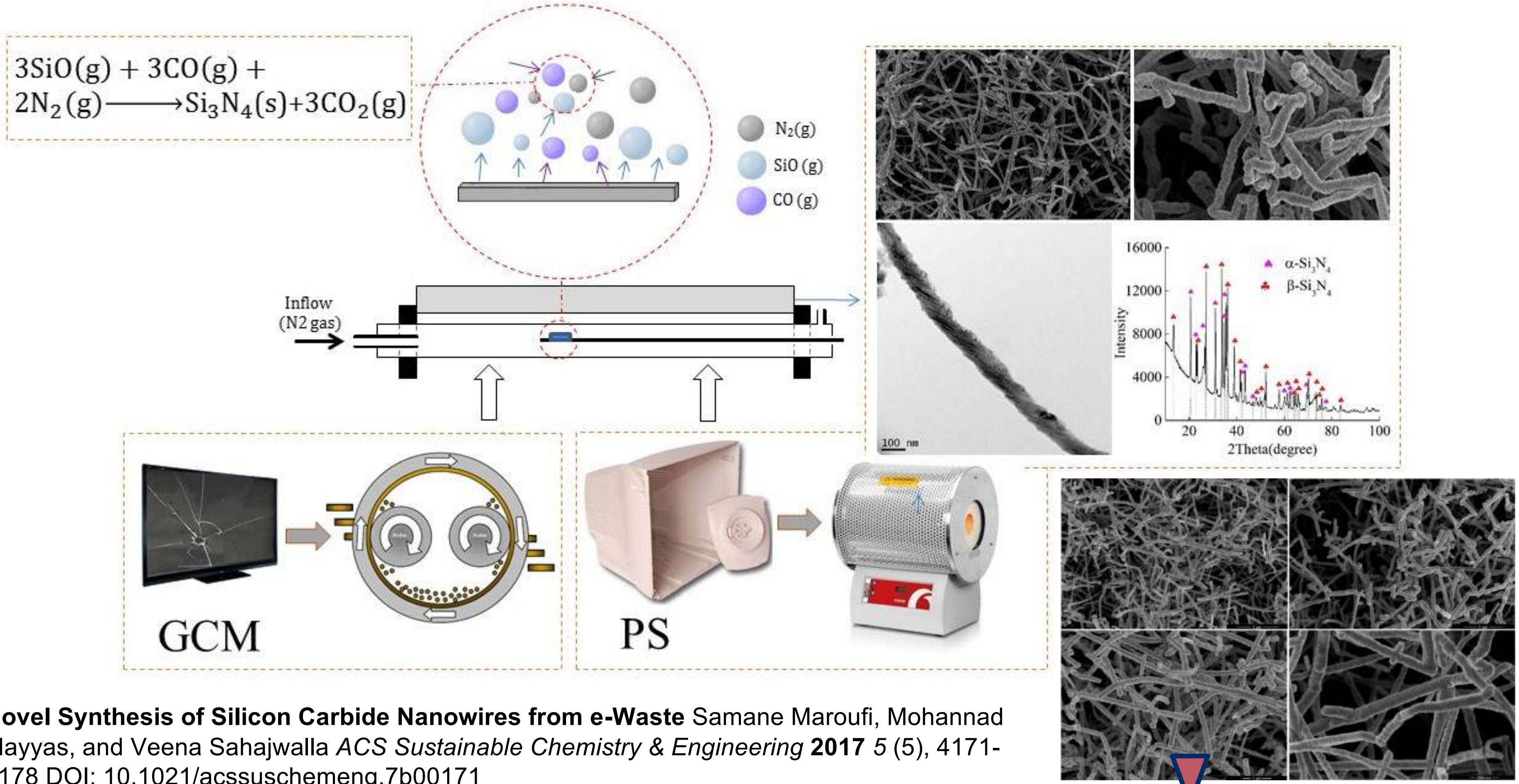




Ali Shokri, Farshid Pahlevani, Katie Levick, Ivan Cole, Veena Sahajwalla, Synthesis of copper-tin nanoparticles from old computer printed circuit boards, In Journal of Cleaner Production, Volume 142, Part 4, 2017, Pages 2586-2592, ISSN 0959-6526

Synthesis of Si_3N_4 Nanowires

Synthesis of Si3N4 nanowires by using the same precursors at different process method



Novel Synthesis of Silicon Carbide Nanowires from e-Waste Samane Maroufi, Mohannad Mayyas, and Veena Sahajwalla *ACS Sustainable Chemistry & Engineering* **2017** *5* (5), 4171-4178 DOI: 10.1021/acssuschemeng.7b00171

E-waste Sample Composition

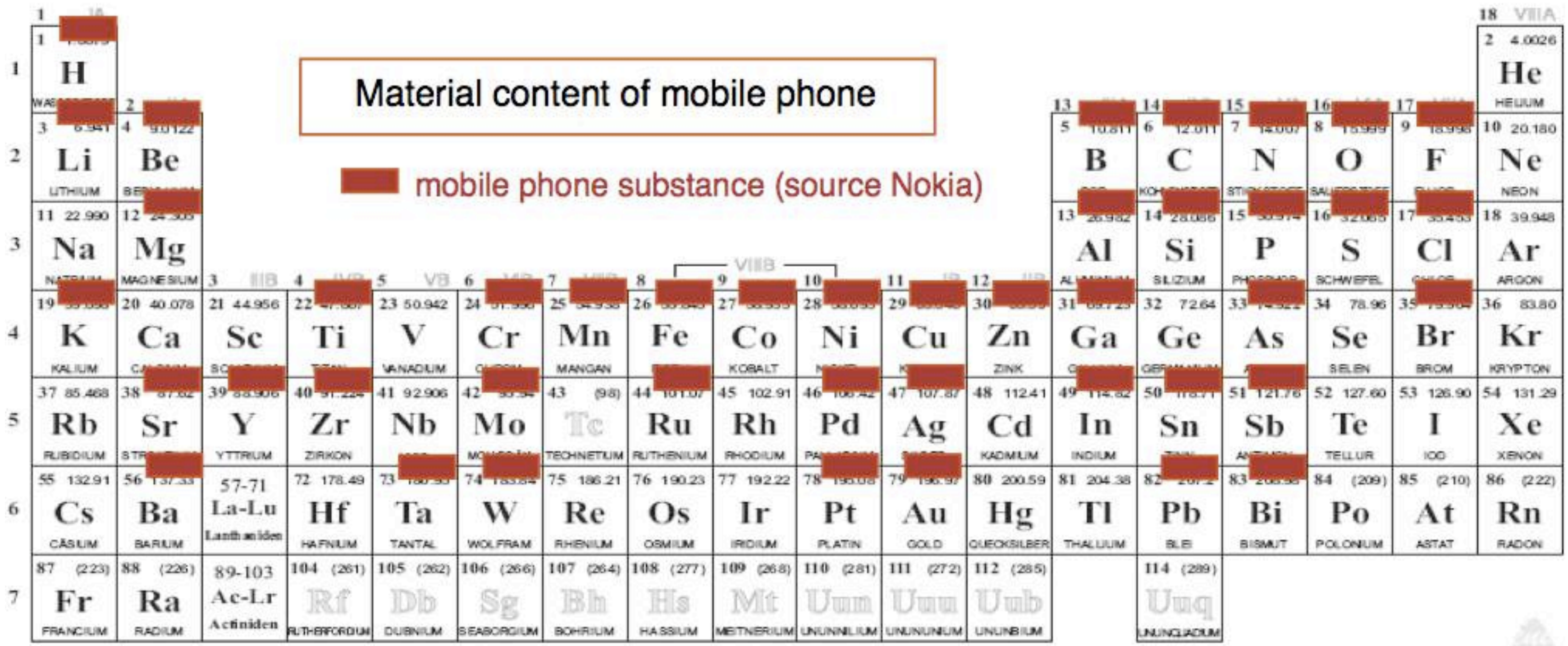




Sample-ID	PCB 1	PCB 2	PCB 3	PCB 4	PCB 5
Al (wt%)	2.75	2.59	0.01	1.74	2.23
Bi (wt%)	0.03	0.01	0.06	0.10	0.02
Ca (wt%)	6.22	5.53	0.02	2.16	4.99
Cr (wt%)	0.01	0.02	0.00	0.01	0.01
Cu (wt%)	19.13	25.08	14.32	5.96	24.79
Fe (wt%)	0.19	0.29	0.54	0.08	0.40
Ge (wt%)	0.02	0.01	0.04	0.03	0.01
Mg (wt%)	0.10	0.07	0.02	0.07	0.09
Mn (wt%)	0.00	0.00	0.00	0.00	0.00
Ni (wt%)	0.07	0.38	0.09	0.06	0.31
P (wt%)	0.01	0.01	0.21	0.00	0.00
Pb (wt%)	0.03	0.03	0.19	3.26	0.44
Pd (wt%)	0.01	0.02	0.01	0.01	0.03
Sb (wt%)	0.01	0.01	0.02	1.22	0.01
Sn (wt%)	3.98	1.59	7.81	7.49	3.60
Zn (wt%)	0.02	0.02	0.00	0.01	0.02

Composition of E-waste

- Electronic waste is a complex mixture, which contains different range of materials
  - Incompatible Polymers
    - 8 – 12 Basic polymers and flame retardant polymers
  - Metal and Oxides
    - More than 30 types of metal and 20 types of oxides

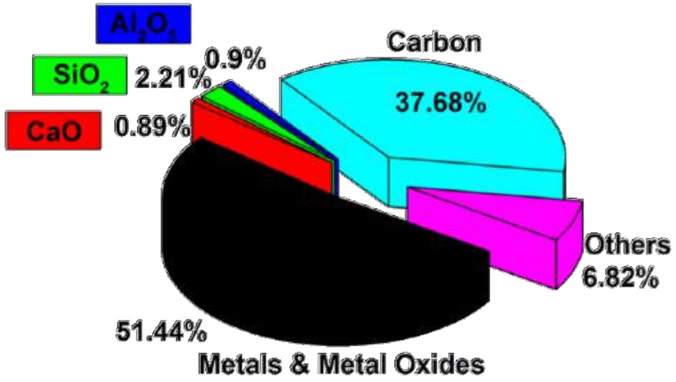


XRF (X-Ray Fluorescence)

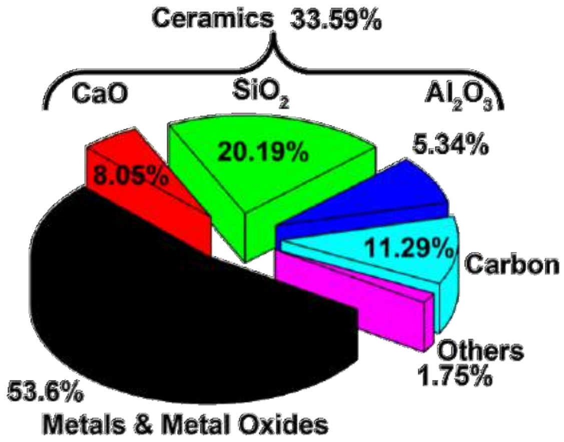
Single-sided WPCB (Monitor PCB)

Multi-layered WPCB

RAW

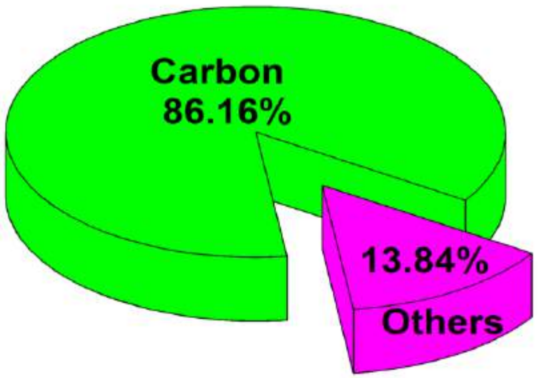


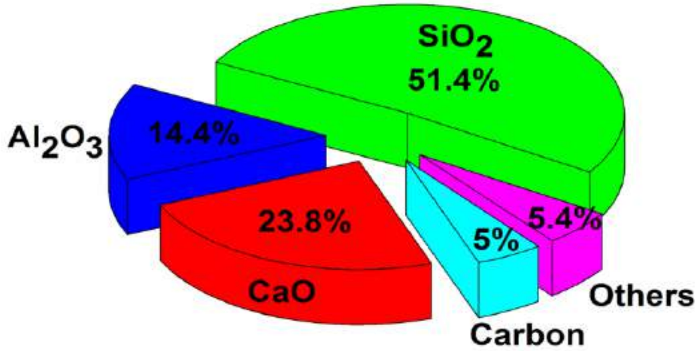
(a)



(b)

RESIDUE





XRF Instrument: PANalytical PW2400 Sequential Wavelength Dispersive X-Ray Fluorescence spectrometry (WDXRF)

Raman Rajagopal, Raghu & L S, Aravinda & Rajarao, Ravindra & Bhat, Badekai & Sahajwalla, Veena. (2016). Activated carbon derived from non-metallic printed circuit board waste for supercapacitor application. Electrochimica Acta. 211. 488-498. 10.1016/j.electacta.2016.06.077.

PCB Elemental Analysis

Elemental analysis of PCBs at different temperatures by ICP. Results are the mean of three independent experiments.

Sample ID	PCB (wt%)	PCB-400 (wt%)	PCB-700 (wt%)	PCB-900 (wt%)
Ni	0.06	0.12	0.08	0.11
Fe	2.8	0.13	0.16	0.19
Zn	0.03	0.02	0.04	0.0
Cu	5.34	9.81	12.66	11.72
Sn	6.89	9.02	9.38	11.09
Al	1.91	2.66	2.63	2.61
Mg	0.06	0.09	0.1	0.11
Ca	1.97	3.4	3.67	4.18
K	0.01	0.02	0.02	0.02
Na	0.05	0.07	0.07	0.07
Bi	0.02	0.04	0.07	0.04
Sb	1.23	2.36	2.57	2.42
Pb	2.96	4.16	5.01	5.21

Transforming e-waste plastic into filaments for additive manufacturing