EMRS Fall Conference in Warsaw 2018

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The Science of "*Microrecycling*": Selective Synthesis of Materials from Waste

Abstract

Waste: A Global Challenge or Opportunity?

The scarcity of raw materials is increasing rapidly. Population increase and changes in consumption patterns combined with the inefficient use of materials push us toward a crisis point. There are many reasons for the current drive for more sustainable industrial processes, including a desire for enhanced social value, lower-energy demand, less waste, and more effective products. To achieve stable long-term growth, something will have to change—and perhaps a new approach based on the materials themselves can help. A new concept for distributed recycling based on *"Microrecycling"* can transform waste into value-added materials.

In conventional recycling, we convert like for like, using glass or plastics to make more of the same. Electronic waste (e-waste) presents a different challenge: its complex parts cannot simply be piled into a giant processing machine and converted back into their original form. Much of this waste ends up in the developing world, where regulation is negligent. A significant proportion of problematic e-waste is also landfilled and stockpiled. In this situation, how can we make sense of this complexity?

The SMaRT Centre focuses on discovering innovative ways of transforming waste streams sustainably to create valuable resources by selective synthesis of materials from waste. We created micro-factories (as small as 50 m^2) for local application in both advanced and developing economies, where metals and ceramics could be synthesised from e-waste without toxic emissions. The technical barriers of conventional e-waste recycling process can be overcome through *"Microrecycling"*. Recent research at the SMaRT Centre has proved that the waste processing in small-scale -*"Microrecycling"*-, enable small operators to convert their waste to value-added materials simultaneously taking the pressure off landfills.

Recovering copper and other metals from electronic waste aren't just sustainable; it's actually more concentrated form in e-waste than in metal ores. The amount of copper found in one ton of printed circuit boards is 10 – 20 times more than that available in one metric ton of copper ore (1). Electronic waste also contains significant amounts of precious metals such as gold, silver, etc. For example, compared with natural gold ores, the gold content in e-waste is significantly higher (more than 20 times (2)), creating an economic driving force for the recycling of electronic waste.

Selective Synthesis of Materials from Waste

The researchers at SMaRT Centre have studied the effects of transformation temperatures for waste resources containing different materials we have discovered

that synthesis of materials from waste is possible by enabling multiple reactions to harness the selective synthesis of various materials. We have laid the foundations for the development of novel *Microrecycling* pathways to generate different materials from waste, using high temperature transformations. Melting, degradation, diffusion or evaporation of different materials are triggered at various temperatures and times. By activating various micro mechanisms; such as, thermal “micronizing”, “nanowiring”; enables the selective synthesis of materials from macro to nano scales at temperatures ranges 400-1550^{o} C.

Selective synthesis of materials makes it possible to transform the glass and plastic together through “thermal nanowiring” at high temperature which generates ceramic products such as silicon carbide nanowires, which have a range of industrial applications (3, 4). In another study, with the glass fraction of e-waste as a rich source of silica (SiO2) and carbon obtained from waste tyres researchers at SMaRT Centre employed fast heating to high temperatures and synthesized excellent quality nano scale SiC (3, 5). We have synthesised MnO and ZnO nanoparticles from spent battery at 900^{o} C via “thermal nanosizing” which have enormous economic and environmental benefits, hence pave the way for sustainable manufacturing (6).

The global supply of rare earth elements (REEs) is under considerable strain, so the recovery of REEs from e-waste is strategically vital. The selective thermal isolation technique makes it possible to recover the rare earth oxides (i.e., Nd, Pr and Dy) from permanent Nd-Pr-Dy magnets sourced from e-waste. Our study has developed a novel oxidation-reduction process to recover REEs from Nd-Fe-B permanent magnets collected from e-waste, using carbon derived from waste tyres as a reducing agent (7). As a rich source of rare earth elements (REEs), Nd-Fe-B permanent magnets were subjected to a low temperature oxidation followed by rapid reduction at high temperature using the activated carbon. This approach resulted in the thermal isolation of REOs from the original magnets.

Using outdated computer printed circuit boards (PCBs), we investigated transformations across a range of temperatures. For example, circuit boards have been selectively transformed into various metallic alloys via thermal transformation, such as copper-based tin, zinc, lead alloys (8-11). For the first time, SMaRT Center’s research invented the direct production of value-added nano particles of metal alloys by selective thermal transformation where degradation of the waste plastics of circuit board created a reducing environment to enhance the processing at much lower temperature of 900^{o}C. Copper-tin nanoparticles were separated from the e-waste while isolation of lead-containing metal occurred also (8). Generation of a new ferrous resource was shown to be possible through the selective thermal transformation, where the toner powder was reduced to produce iron (12).

Automotive shredded residue (ASR) waste plastics are difficult to recycle and hence contribute significantly to environmental problems (13). On-going research of SMaRT Center has already proven that selective thermal transformation safely converts ASR through its reform into graphitic carbon and nano-ceramics (13). This and other selective synthesis of materials have the potential to produce value-added resources that have substantial economic and environmental benefits.

The Science of "*Microrecycling*"

The selective synthesis of materials based on high-temperature thermal transformation, will open novel pathways, not only to recovering valuable materials but also to generating new resources for industrial use. This adds further interpretation to materials sustainability which transforms end-of-life materials that cannot be reused or recycled in a conventional manner- the new solution proposed is - *"Microrecycling".*

"*Microrecycling*" opens up pathways for innovative supply chains by creating new resources through lateral integration. For example, silica from e-waste and carbon from end-of-life car tyres can make industrial grade nano scale SiC (3, 5). Another study suggests that the styrene acrylonitrile plastics from end-of-life printers can potentially be used as a partial replacement for conventional carbonaceous materials in iron oxide reduction, enabling an alternative sustainable pathway for production of iron (14).

"*Microrecycling*" has proven that, graphitic carbon and nano-ceramics from Automotive Shredder Residue (ASR) (13) could be used to generate ultrahard ceramic surface on steel to enhance the mechanical property (15, 16). Although the methods of adding extra alloying elements have proven effective in improving the performance of more expensive, high grade steel components, they are not economically viable for relatively low cost steel products. New options are needed. Our study on industrial grade steel at the macro to nano scale reveals that, intense deformation enables various micro mechanisms that transform the normal steel into a new grade of steel with ceramic-like hardness and metal-like toughness (17-19). Alternatively, complex industrial waste streams can be transformed in-situ via precisely controlled high temperature reactions to produce an ultrahard ceramic surface on steel. By modifying the composition of the waste input and the processing parameters, the ceramic surface can be effectively customised to match the intended application of the steel. In one study, we invented a sustainable approach to fabricate protective nanoscale TiN thin film on a metal surface by using automotive waste plastics as titanium and carbon sources (16), in another study; we created an ultrahard ceramic surface on steel (15).

Our investigation discovered that the chemical bonding and structural continuity from the base metal to ceramic layer which distinguishes this from other types of conventional surface coating technology, where metals and ceramics are mostly bonded such that there is no structural continuity. This innovative approach, "*Materials Microsurgery"*, is to devise a new, more cost-effective process to increase the hardness of metal by producing an ultrahard ceramic surface and hard near-surface structure without affecting its bulk properties. This can provide a pathway for the development of cost-effective high-performance surfaces for metals which might not otherwise have desirable surface properties, for a broad range of industrial applications.

The focus of conventional recycling is very limited, for example, conventional e-waste recycling focuses mainly on metals recovery, the bulk of the remaining waste materials, including the glass and plastics, is often incinerated or landfilled due to the lack of an efficient and cost-effective means of processing. The large volumes of glass and plastic within e-waste, therefore, represent both a significant global waste burden and a potentially valuable, untaped resource. Within "*Microrecycling*", sustainable operations could convert the waste materials into products or input for another manufacturing process. This approach of sustainable materials research creates win-win outcome for Engineering, Environment and Economics and goes beyond conventional recycling and supply chains.

Microfactory technology

"Microrecycling" based technology could be set up almost anywhere in the world via microfactory. This science and technology can potentially protect the environment from the undesirable impacts of landfilling toxic waste streams, reducing burdens on natural resources and enabling manufacturer's access to secondary resources that would otherwise be sourced from more and more expensive raw materials. *"Micorecycling"* could transform waste into value-added materials at a local level and contribute to global supply chains. They could form pathways for micro-economies, based on materials production in green microfactories, to develop and generate jobs of the future. They will create local economic opportunities by allowing multiple small-scale operators to generate value-added resources, by reforming waste. This offers new solutions for transformation of waste materials into value, reducing waste pollution, and ultimately eliminating negative social consequences of waste in many disadvantaged communities globally.

"Microrecycling" opens up a new approach *"Materials Microsurgery"*

We propose a radical, new approach to the problem of managing our growing, global flood of e-waste- *"Microrecycling"*. Our research seeks to understand how the many components of e-waste behave, at the molecular and nano-levels and how the reactions triggered by controlled heat can be beneficially employed. Several micromechanisms in *"Microrecycling"* deliver innovative solutions for the ubiquitous, high volume and potentially toxic waste and opens alternative pathways for the recovery of valuable materials from waste.

We have proposed this as a new approach for materials transformations, *"Materials Microsurgery"*, where we are working towards new surfaces on materials to address properties not possible by the parent materials, like providing nano-ceramics on steel. So the steel has a ceramic like property which has never before been possible.

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