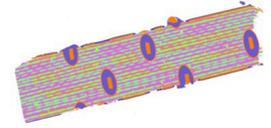


Feature



Mining metal from waste

With the transition to a low carbon future and increasing technological applications, the global demand for metals will continue to rise into the foreseeable future. However, primary ore deposits are finite, and to continue production, lower grade and more complex ore deposits need to be discovered, evaluated and exploited, with increasing exploration and production costs. Additionally, there are significant geopolitical constraints on global resources for some critical raw materials and metals, along with ethical constraints of ‘off-shoring’ minerals supply to areas of the world with poor records in terms of legal mineral production, human rights violations, health and safety, and the long-term environmental impact of mining. Whilst it is unlikely at present to be able to fully meet supply needs, one source of metals for the future is through recycling of both domestic and industrial waste. Modern waste streams such as end-of-life lithium-ion batteries and electrical waste commonly contain significantly more metals than primary ore deposits before processing. However, these waste materials are complex, and through two case studies in this article, we focus on how methods commonly used in modern mining and mineral processing can be used to assist the processing and recovery of metals from waste. Perhaps it is time to reclassify waste as valuable resources for the future.

Recovering metals and other commodities from waste is not new; the old British proverb ‘*where there’s muck there’s brass*’ is as true today as in the past. It generally means that there is money to be made from unpleasant or dirty jobs and is perhaps exemplified in the past in the United Kingdom by nineteenth century rag-and-bone men, who collected unwanted scrap for recycling (Fig. 1). Today’s equivalent is that waste from the developed world is trans-shipped to the developing world for recycling or disposal (Fig. 1). In modern terms, the 3Rs of sustainability (Reduce, Reuse and Recycle) are an attempt to mitigate the global impact of our consumer demand and the resultant waste streams it generates. Society has always generated waste; what has changed with time is the nature of that waste and the volume of it. In parallel with this, mining has played a pivotal role in the supply of raw materials, including metals, to meet global demand. As technology changes, the supply of different raw materials adapts to meet that demand; for example, at present, there is a significant focus on the supply chain for critical raw materials, which are needed for current and future technologies. However,

ore deposits form on geological timescales and consequently are not replenished at the same rate as mineral production—in other words, the global supply of metals is essentially finite. Moreover, many of the easy to find, near-surface mineral resources have already been discovered and exploration is becoming more costly and a greater risk to investors and mining companies. Current trends to a low carbon future, driven in part by climate change, combined with technological developments are leading to increased demand for minerals and metals. So, is it time to look again at how to mine metals from waste and also to consider waste as a valuable resource for the future?

Natural resources needed for a low carbon future

The clear and urgent need to transition to a low carbon future, as illustrated by the reports of the International Panel on Climate Change (IPCC), thereby limiting the rate of greenhouse gas emissions and temperature rise is well-established. It is argued that one critical area in

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which to achieve the transition to a low carbon future is through vehicle technology. For example, the present UK Government is committed to net-zero carbon emissions by 2050. In 2023, transport was responsible for 29 percent of total UK greenhouse gas emissions, and over half of that came from cars and taxis. To meet net-zero targets, in April 2025, the UK government confirmed an end to the sale of new pure petrol or diesel cars in 2030 and an end to new pure petrol or diesel vans in 2035, with the sale of hybrid cars only permitted between 2030 and 2035. The year 2040 was proposed as the 'backstop' phase-out date for new non-zero-emission vehicles of all other types, including heavy goods vehicles and buses. Whether or not this target is achievable depends not only on politics and policy decisions but also on the availability of mineral resources. Existing battery technologies are dependent on geological natural resources such as carbon, copper, aluminium, lithium, cobalt and nickel. Currently known sources for some of these raw materials are insufficient to supply future predicted demand. In mineral exploration, there is usually at least a 7- to 15-year lead time from the initial exploration for potential mineral deposits, through to the determination of the potential ore reserves and ultimately the opening of a mine. If we are to meet the future predicted demand for raw materials then there needs to be a significant increase in exploration for new deposits, which is also challenging at a time when universities struggle to recruit students to geoscience degrees. To meet this gap in supply, we need to consider alternative sources of these raw materials, possibly from waste.

Sustainable and ethical mining

It could be argued that the concept of 'sustainable mining' is a bit like the emperor's new clothes—at its most basic level, it cannot be true. Other than pos-

sibly naturally replenishing lithium brine deposits, mineral deposits do not form over timescales that are short enough for the extracted ores to be geologically replaced. Whilst changing technological demand has led to different raw materials being extracted over time, for many commodities mined for millennia, such as copper, what we see is a progressive reduction in the abundance of the valuable commodity (the ore grade) over time. Many copper ore deposits today may have an overall grade of ~0.5 percent copper; 100 years ago, that value was typically 1–2 percent. In addition, changing processing methods and technology mean that minerals that could not previously be successfully economically processed to recover the metal of interest now can be. If we accept that ore deposits are finite, then we need to ensure that when they are mined, we can successfully extract as much of the commodity of value (i.e. waste as little of the minerals of value as possible). This has a positive impact on the economics of a mining operation, but is also critical for sustainability. Whilst there are examples of successful operations where historical mine wastes have been reprocessed with improved technology linked with increased commodity prices, in general, once mined, unrecovered minerals of value are lost. Thus, sustainable mining should focus on ensuring that mineral recovery from an ore body is as efficient as possible, whilst also being cost-effective and incentives are needed to ensure companies recover all of the minerals of value present. This requires very detailed understanding of the ore body, allowing detailed resource evaluation, careful mine design and effective mineral processing. Geometallurgy is a critical part in modern mining and mineral processing, where detailed applied mineralogy, using modern analytical systems, is used to design a mineral processing circuit, which maximizes recovery and reduces waste. Furthermore, once

Fig. 1. (a) Historically, in the United Kingdom, 'rag and bone men' would collect waste for recycling (Image courtesy of Tor605, Newcastle Libraries, CCO 1.0). (b) Today, much waste is shipped to the developing world where it is sorted by hand; the image shows electronic waste at Agbogboshie, Ghana. (Image courtesy of Muntaka Chasant, CC BY-SA 4.0.)

processed and refined, we also need to think about how to sustainably use these raw materials during their product life cycle. Knowledge from applied mineralogy and mineral processing can equally well be applied to our understanding of how to recycle products at the end of their (first) life cycle. Commonly product design is focussed on form and function; yet, increasingly, we also need to consider end-of-life recycling during the initial product design, such that each component used can be separated using available processing technology, and therefore reducing the cost of recycling.

A further challenge to mining and mineral supply is that the spatial distribution of mineral deposits around the globe is controlled by geology; many critical resources may be located in countries where corruption is rife, thereby presenting increased levels of risks for exploration, investors and miners. However, there are a wide range of other constraints (known as 'modifying factors'), which also determine whether or not an ore deposit becomes a viable mining operation. Constraints may include energy costs, labour costs, environmental restrictions, land ownership, perception of mining within society, corruption and operationally active cartels or criminal gangs. In the United Kingdom, metal mining was historically very significant in areas such as the polymetallic ore fields of SW England, the lead-zinc mining districts of the Pennine ore fields of northern England or the copper mines of Parys Mountain in North Wales. Many of these ore deposits have been worked out and the mines long since abandoned, but today there is also a perception that mining is something to be carried out somewhere else in the world—'*out of sight and out of mind*' and '*not in our own backyard*'. Many former mining regions are in areas of outstanding natural beauty, even though,

paradoxically, the remnants of mining activity are now an integral part of that landscape. If we can extract raw materials locally, then surely there is an ethical requirement that we do so. For example, Finland is a stunningly beautiful country with large areas of wilderness; it also hosts very significant mineral deposits for many current and possibly future commodities such as gold, cobalt and nickel. There is a strong ethical argument to support mining locally, rather than importing raw materials from developing countries where the environmental and legal controls on mining are much less stringent than in the developed world, although it should also be borne in mind that such operations provide critical employment and income to the developing countries. Within the European Union, the 2024 Critical Raw Materials Act has set a series of ambitious benchmarks for strategic raw materials, which amongst others includes the need that at least 10 percent of the EU mineral consumption would be mined within the EU by 2030 and also 25 percent of raw material supply via recycling within the EU by 2030.

A second issue in ethical mining is the current scale of illegal mining; the illicit trading of minerals and associated crimes such as theft, fraud, adulteration, substitution and smuggling. Illegal mining is mineral extraction outside of the regulatory control of the state. Typically, in illegal mining, the workforce may be being exploited; the mining operations may have poor safety standards; there may be no environmental controls in place and the revenue generated often largely falls into the hands of criminal cartels or corrupt regimes (Fig. 2). Even if we ignored the exploitation of the workforce, environmental damage and criminal use of the money generated, illegal mining is also very poor in terms of the sustainable use of mineral deposits. Inadequate mine planning, extraction and ore processing means that such operations achieve very poor mineral recovery and can impede later successful legal mining operations by sterilizing areas of mineralization. Theft and fraud can also impact the sustainable use of mineral resources. Ways in which crime can occur in mining include the theft of an ore concentrate and its substitution with another material to 'replace' the mass of stolen material. Many smelters and industrial plants require a very tightly and clearly defined mineral product specification, and if ore concentrates are adulterated with wastes, the whole consignment may be 'contaminated' with the so-called penalty elements (undesirable elements that can have a negative impact on the final products, and therefore lead to increased costs, or operational problems, during processing or smelting).

In part due to the scale of illegal mining and the use of revenue generated through such activity in the support of criminal activity, global terrorism and the support of corrupt regimes, there is increasing legislative control in terms of understanding the original source,

Fig. 2. Artisanal cobalt miners in the Democratic Republic of Congo are pictured working with little, if any, health and safety measures. (Image courtesy of the International Institute for Environment and Development, CC-BY-2.5.)



or provenance, of minerals. One group of commodities, tin, tungsten, tantalum and gold (the '3TG' minerals), and referred to as conflict minerals, are a case in point. On 1 January 2021, the European Union conflict minerals regulations required companies to be able to demonstrate that they have undergone supply chain due diligence checks to ensure that any conflict minerals, or commodities derived from them, have been sourced from legal mining operations. These regulations at present only affect tin, tungsten, tantalum and gold; however, other raw materials critical in the battery supply chain, such as cobalt, mined in places such as the Democratic Republic of the Congo (DRC) and surrounding countries, may increasingly come under intense scrutiny in terms of companies being required to demonstrate that raw materials used in their products are sourced ethically from legitimate mining operations.

Waste as an alternative source of metal

If we accept the proposition that ore deposits are finite and that there are challenges associated with sustainable and ethical mining, should we look in more detail at the potential of recovering metals from both domestic and industrial waste streams? Waste streams can either be generated at the start of a product's life as part of the manufacturing process or be formed at the product's end of life when it is discarded. For example, phosphogypsum is a waste from the production of phosphoric acid from phosphate rocks for fertilizer production. It is estimated that there are 5 to 7 billion tonnes of phosphogypsum worldwide, with an additional 300 million tonnes produced annually. Whilst there are a range of potential uses for phosphogypsum (primarily plasterboard and associated building products), it has a typical concentration of rare earth elements (REE) of 0.4 percent and research is ongoing to determine how best to recover these critical raw materials from this waste material.

At the other end of a product's life, we have wastes such as lithium-ion batteries (LIBs) and electrical waste including printed circuit boards. With the increased global demand for personal electronic devices (e.g. smart phones, computers and flat screen televisions), along with the energy transition away from conventional fossil fuels to electric vehicles (EV), it is predicted that there will be an enormous growth in demand for LIBs (a transition known as the 'battery revolution'), with the market value of LIBs being nearly 200 billion USD in 2025, but projected to increase to more than 420 billion USD by 2033. Whilst there are a wide range of potential geological sources of lithium (e.g. from evaporative concentration of brines and lithium-bearing minerals in pegmatites), other materials used in battery construction, such as cobalt, are much less common, and cur-

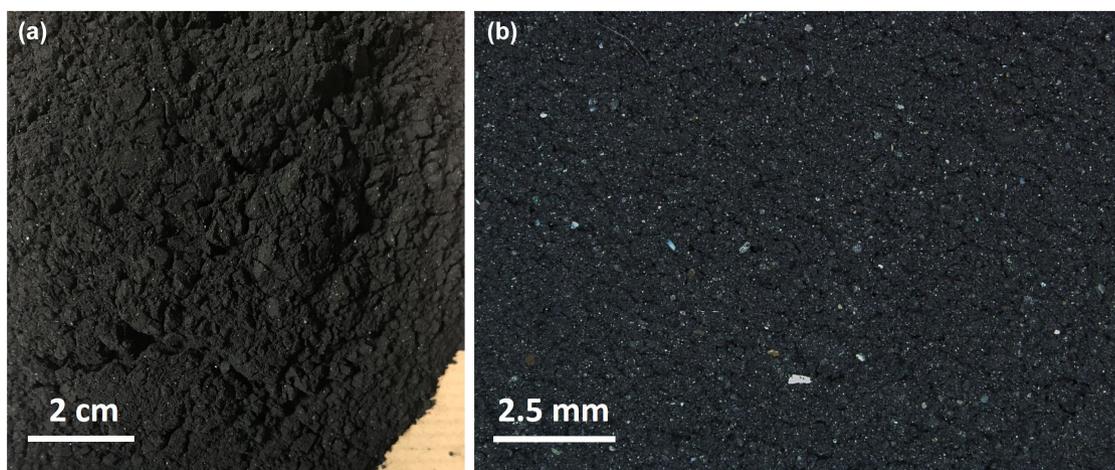
rent production is focussed on areas in Central Africa, where illegal mining is a significant challenge. Consequently, there is huge potential for the recycling of LIBs with a projection that 4 million metric tonnes of LIB waste from EV batteries could be generated from 2015 to 2040. In addition to lithium, LIBs contain other valuable components such as graphite, cobalt, copper and nickel. Personal electronic goods also generate significant volumes of electronic waste (E-waste) with estimates suggesting that in 2022, 62 million tonnes of waste was generated worldwide but this is projected to increase by 2030 to an annual global waste stream of 82 million tonnes. Disposal of this waste through incineration or landfill poses significant environmental risks, but this E-waste contains a range of high value elements such as gold, silver, platinum, palladium, copper, tin and aluminium often at abundances far greater than in natural ore deposits. In 2022, only about 22 percent of the annual production of E-waste was collected and recycled.

The challenge associated with both waste LIBs and printed circuit boards is that the materials are complex and multi-component, containing both potentially valuable commodities and materials that would be viewed as penalty elements restricting the value or potential of the material for smelting. However, it could be viewed that this is no different to mineralogically complicated ore deposits, which are themselves difficult to process. So, can we use the same advanced analytical methods adopted in geometallurgy to understand complex waste streams? Bulk chemical analysis alone provides valuable data on what elements are present and at what abundance, but does not provide an understanding of what phases those elements are present in, or information on their size, shape, morphology, texture or material association; such information is critical if we need to process and separate the different components before recovering the metals. Modern methods used in mineralogy allow us to understand a material not just at high resolution not only in 2D but also in 3D and through repeated analysis during processing, effectively in 4D. Recent research has highlighted that no single analytical method can provide all of the required data in these complex materials; instead, an integration of different analytical tools is required. To illustrate this approach, we summarize recent work on recycled LIBs and waste printed circuit boards.

Recycled lithium-ion batteries (black mass)

Following the removal of residual electrolyte, end-of-life LIBs undergo a physical, thermomechanical process to produce a fine powder known as 'black mass' (Fig. 3). The removal of electrolyte is a critical step in the process as if present, the batteries could spontaneously combust, ignite or explode; most commercial

Fig. 3. (a) Hand specimen and (b) binocular microscope image of black mass—powdered recycled lithium-ion battery waste. Note the lack of obvious variability at this scale of observation.

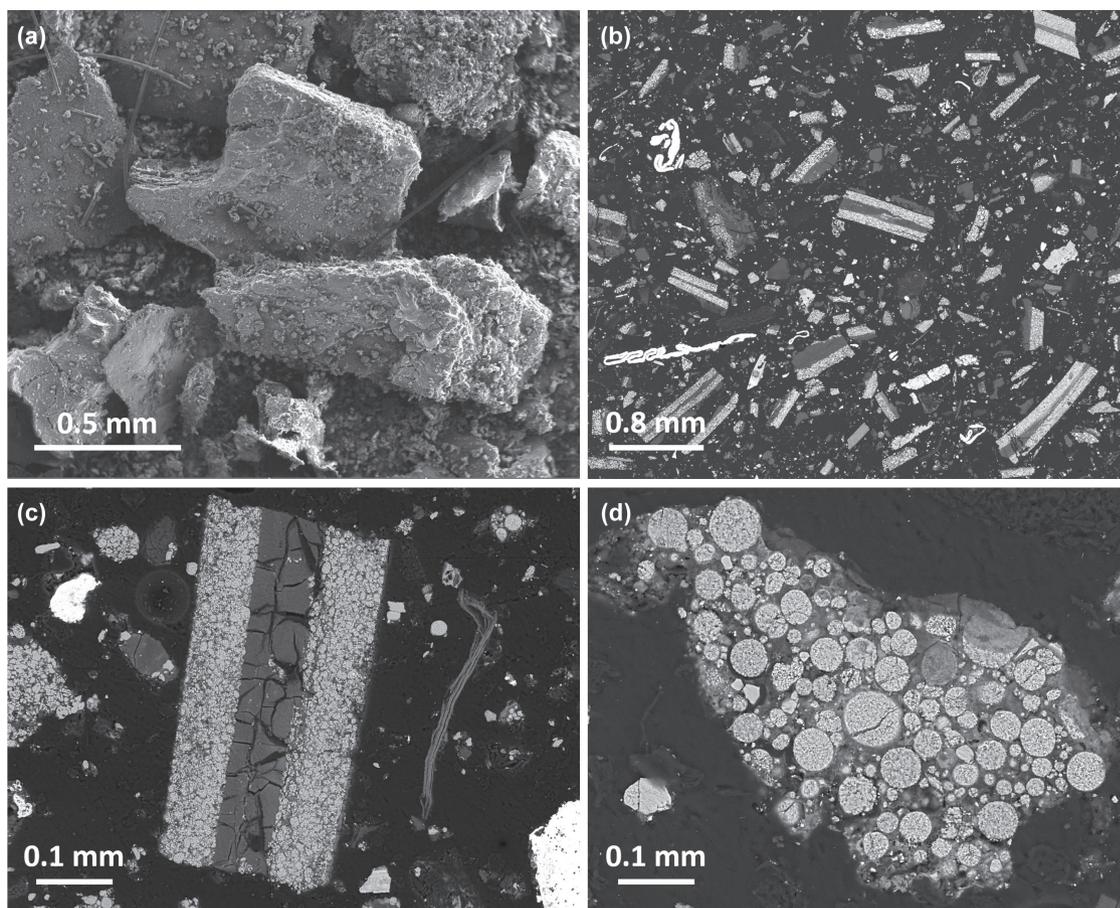


electrolytes comprise a mix of electrolyte salts such as lithium hexafluorophosphate (LiPF_6), lithium tetrafluoroborate (LiBF_4), lithium perchlorate (LiClO_4) and additives in organic solvents, all of which have a considerable potential environmental risk. Black mass could provide an alternative supply of battery metals, including cobalt, lithium, manganese, nickel and copper, whilst also reducing the need for waste disposal. The initial powder is typically very fine grained, and its macroscopic appearance obscures its complexity, being homogenous at the visible scale, but highly heterogeneous at the micron scale (Fig. 3). The LIBs comprise cells with a cathode and an anode with a polymer separator. Most commonly, the anode comprises copper foils and spheroidized natural graphite, whilst the cathode is usually made up of lithium metal oxide particles on aluminium foil. These cell components are tightly packed and adhered together with an organic binder. The LIB components, which may be present within a black mass powder in terms of their functional form, comprise the following: (1) the casing; (2) graphite; (3) aluminium foil; (4) copper foil; and (5) lithium metal oxides. The lithium metal oxides making up the cathodes are divided based on their chemistry into five main types: (1) NMC (LiNiMnCo oxides); (2) LCO (LiCo oxides); (3) LM(N)O (LiMn(Ni) oxides); (4) LFP (LiFe phosphates); and (5) NCA (LiNiCoAl oxides). As the recycling feed material for reprocessing may have been derived from multiple sources, any single batch or waste stream is likely to be heterogeneous, consisting of variable mixtures of these different components. In addition, different batches of this feed material are also likely to be variable, again reflecting the different sources of the recycled batteries. This will only get more complex with time as designs change and new battery chemistries are developed. For example, the Co content of cathodes has progressively dropped, broadly in line with the metal price, and Na ion batteries currently in development require carbon rather than graphite anodes.

This black mass powder is effectively a tradeable commodity, the value of which is controlled by its physical and chemical characteristics. The bulk chemistry provides a quantitative analysis of the elements present and their abundance, but lithium, being a light element, cannot be detected using instruments such as X-ray fluorescence (XRF); hence, analysis for lithium is usually carried out using inductively coupled plasma mass spectroscopy (ICP-MS). Texturally, the black mass powder comprises complex multi-component particles. The overall morphology of these particles cannot be seen through binocular microscopy as it is too fine grained, but can be imaged using scanning electron microscopy (SEM), either as particles mounted unprepared on SEM stubs or where the samples are embedded in resin, and then cut and polished to form sections or blocks (Fig. 4). Whilst the SEM imaging of the 3D particles reveals particle shape, SEM backscatter electron imaging in cross section (where the grey scale relates to the atomic number of the material) reveals the complexity of the individual black mass particles (Fig. 4). SEM imaging can provide particle textural information (shape, size, etc.) along with spot chemical analysis through energy dispersive spectrometry, although again lithium cannot be detected directly.

Particle shape can be imaged in 3D by using micro-computed tomography (microCT). For example, copper, which has the appearance of linear particles in cross section in polished SEM blocks, can be shown to be thin, complexly folded sheets when viewed using microCT (Fig. 5). Particle textural information alone does not allow the cathode particle types to be determined, nor their relative abundance assessed. However, this can be achieved through automated SEM-EDS particle analysis. Samples are prepared by mounting them in resin then cutting, polishing and carbon coating the surface. These particle mounts are then compositionally mapped within a scanning electron microscope with the rapid acquisition of energy dispersive chemical spectra (EDS). Effectively, the composition of the particles is mapped,

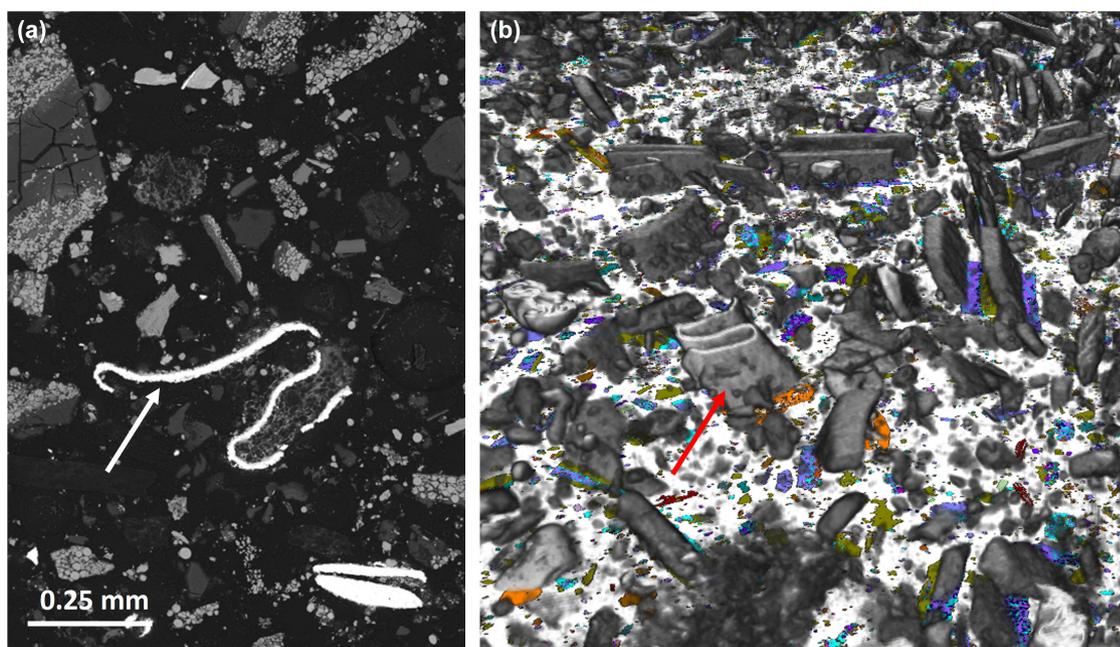
Fig. 4. Lithium-ion battery 'black mass' scanning electron microscope images. **(a)** SEM secondary electron image black mass particles. **(b)** SEM backscatter electron image—cathode particles are complex multi-component materials; copper appears as complexly folded sheets. **(c)** SEM backscatter electron image of a cathode particle composed of Ni-Mn-Co and minor Cu oxides (NMC cathode). **(d)** SEM backscatter electron image of a cathode particle composed of Mn-Ni oxides (LMNO cathode).



pixel-by-pixel, with each analysis point assigned to a chemical category. Whilst the element lithium cannot be determined directly, the different lithium

metal oxide types can be identified based on the relative abundance of the other elements present. In this way, through automated SEM-EDS analysis, the abundance

Fig. 5. MicroCT imaging of black mass helps to identify the particle 3D shapes. Here, copper, as seen under **(a)** SEM backscatter imaging of a polished surface (bright particle arrowed), can be seen **(b)** in the microCT image to be a folded sheet (arrowed).



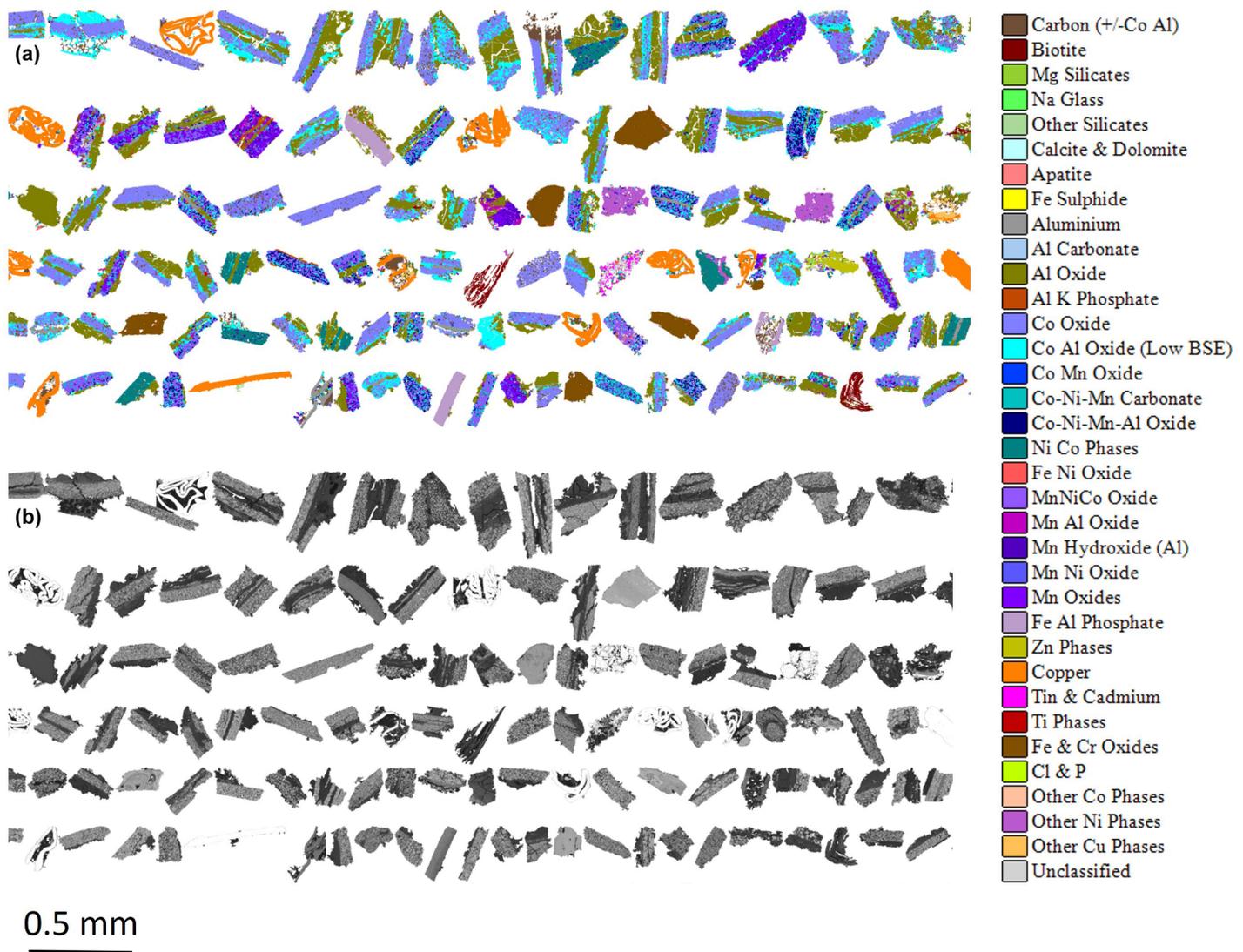
of all of the materials present in a sample of black mass can be quantified. Whilst identifying the abundance of these components, the automated SEM-EDS analysis also provides particle compositional maps, allowing data visualization (Fig. 6), which can be compared with the SEM imagery. The inferred particle composition based on the automated SEM-EDS analysis can be cross-validated using spot chemical analysis via laser ablation ICP-MS (LA-ICP-MS). The chemistry of individual particle types can thus be analysed; lithium can be detected and its relative abundance in different particle types determined and compared with the identified particle types.

Waste printed circuit boards (PCB)

Current estimates suggest that in 2022, 62 million tonnes of E-waste was generated. This is projected to increase by 2030 to an annual waste stream of 82 million tonnes (based on a UN report, the 62 million tonnes

of E-waste generated in 2022 would fill 1.55 million 40-tonne trucks, roughly enough to form a bumper-to-bumper line encircling the equator). In terms of metal content, the most valuable component of E-waste is printed circuit boards (PCB), estimated to make up anywhere between 2 and 7 percent of the total E-waste. The printed circuit boards are themselves multi-component and typically composed of approximately 30–50 percent metals and 50–70 percent non-metals (including glasses, plastics and ceramics). The metal fraction is dominated by copper, aluminium, iron, nickel, lead, tin, zinc, antimony and precious metals such as gold, silver and platinum group metals. The precious metals are of particular interest; for example, based on their gold content, PCB wastes have been classified as low (100 ppm), medium (100–400 ppm) and high (>400 ppm) grade—in comparison, albeit the tonnages are much larger, most gold mineral exploration targets would have an equivalent gold grade of ~5 ppm.

Fig. 6. (a) Automated SEM-EDS (AMICS) particle images of black mass showing particles mapped based on their chemical composition along with (b) the corresponding particles as seen in SEM backscatter electron images. Note that in this image, the Cu metal particles are 'white'.



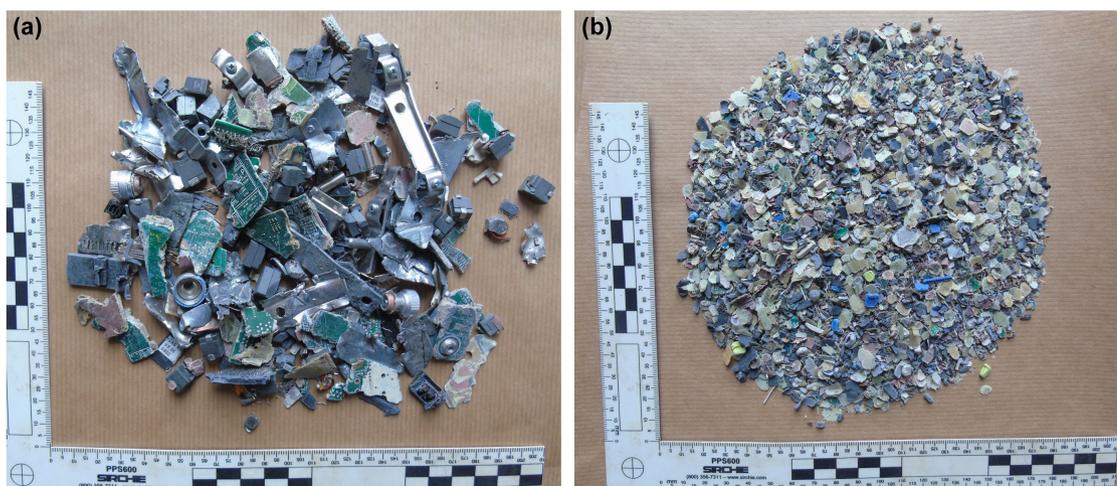


Fig. 7. Photographs of waste printed circuit boards (a) material following magnetic separation and (b) shredded printed circuit boards.

E-waste is more complex and more variable than LIB black mass, being a function of the materials being recycled. At present, it goes through a series of stages including disassembly, size reduction through shredding and grinding, separation (including both mechanical separation but also chemical separation) followed by metal recovery (using pyrometallurgy, hydrometallurgy, bio-hydrometallurgy and electrochemical processing) before finally, metal refining. One of the challenges with this complex material is that whilst there are a range of valuable components present, there are also the so-called penalty elements (e.g. in copper smelting, arsenic, mercury and fluorine are penalty elements), which would

affect the potential value and use of the material during smelting and refining. In addition, there is a need to be able to effectively separate the valuable metals from the other components; this can be as simple as acid dissolution of the copper tracks or as complex as recovering the antimony used as a fire retarding agent in the circuit board substrate. We have again applied a geometallurgical approach to characterizing waste shredded PCB to determine a methodology, which would aid in the design of an optimized waste processing circuit to recover the metals of value.

Most shredded printed circuit boards are initially coarse grained and multi-component. Binocular micros-

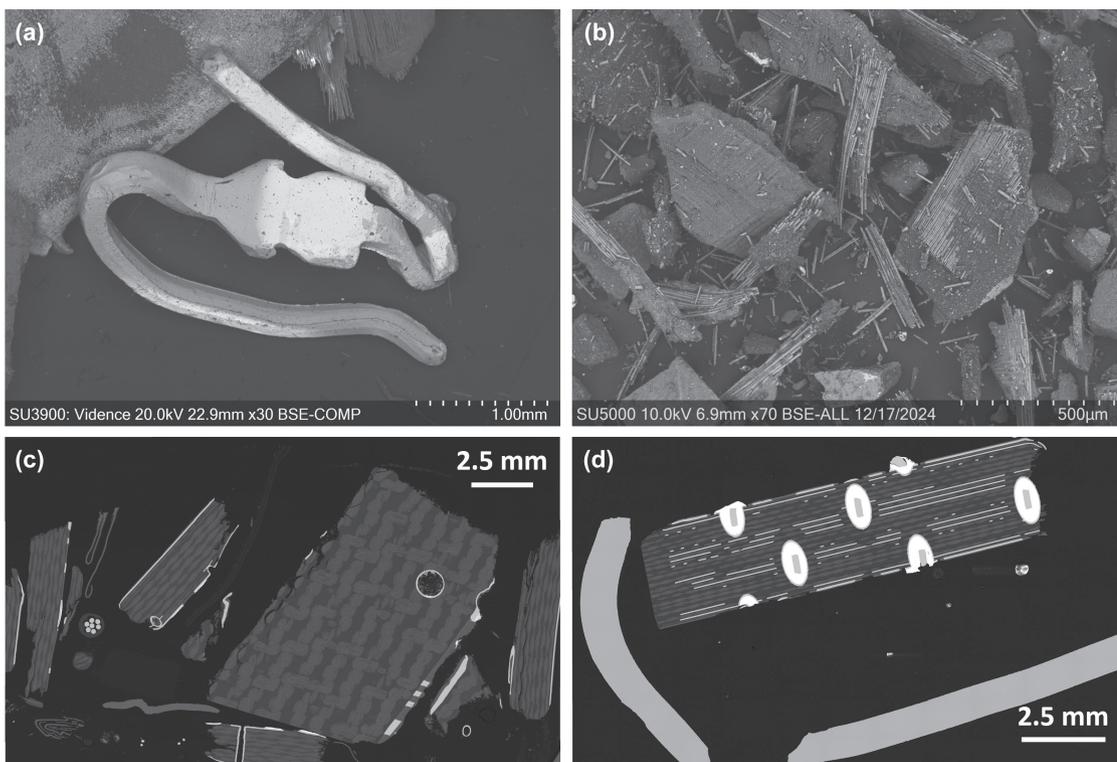


Fig. 8. Scanning electron microscope images of waste printed circuit board samples. During the shredding of the original printed circuit board, metal fragments become folded (a) and glass fibres are released from the boards (b). (c, d) SEM backscatter images of PCB particles; the grey scale reflects the average atomic number of the component material, such that metals will be lighter grey. Note the complexity of the fine scale structures and the distribution of metals within the particles.

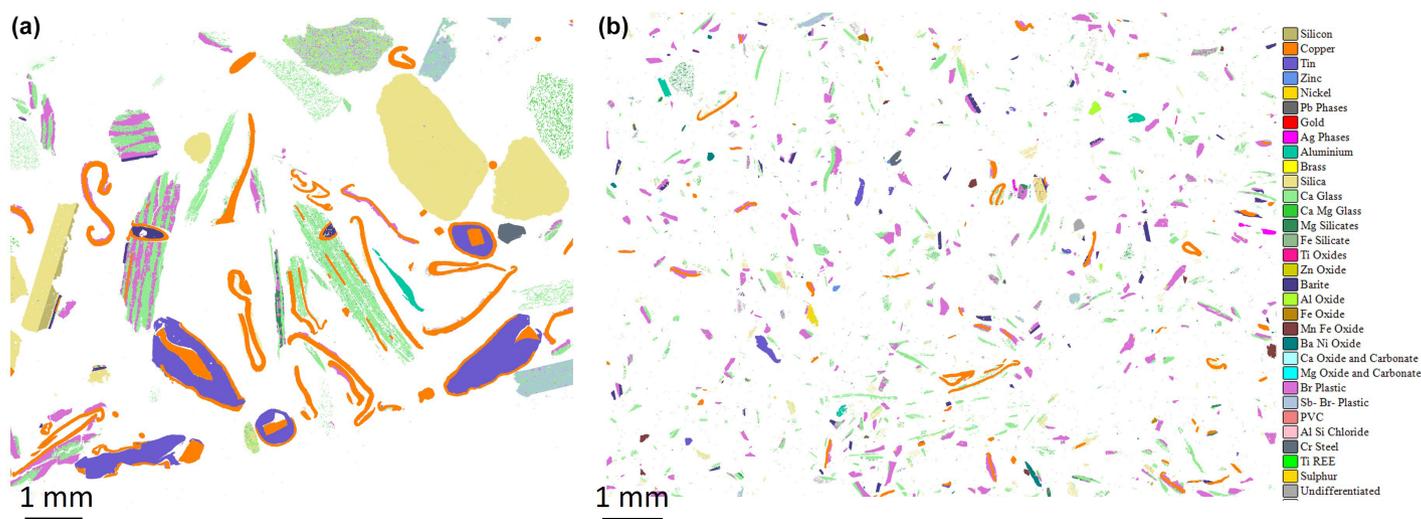
copy alone provides little useful information (Fig. 7) other than the material size, shape and component parts, whilst manual scanning electron microscopy is also restricted due to the particle size, but does illustrate how the initial material behaves during shredding. In particular, it is apparent that because the metals are malleable, metal sheets become folded during shredding, which may affect how the particles behave during later separation (Fig. 8). In addition, within the finer size fractions of waste PCB, numerous glass fibres are formed as a result of degradation of the boards (Fig. 8). Samples of the shredded printed circuit boards can also be mounted in resin, cut and polished and then analysed using both manual and automated scanning electron microscopy. Particles are typically tabular in form, so can be mounted and cut so that the cross section area can be measured. SEM backscatter electron images of polished sections through waste PCB particles are shown in Fig. 8. These images highlight the complex very fine resolution construction of the printed circuit boards, with different metal types present both on the surface of the fragments but also embedded within the particles (Fig. 8).

Based on automated SEM-EDS analysis, the particle types present and their relative abundance can be determined. In our initial work, the more common particle types present include: (1) metals (copper, tin, aluminium, brass, chromium-steel, aluminium oxides and lead phases); (2) plastics (bromine-bearing plastics and antimony-bromine plastics); and (3) glasses (silica, calcium glass and calcium magnesium glass), along with a wide range of other particle types. This method can determine what metals are present, how abundant they are and in what particle types they occur. A limitation, however, is that commonly in coarser grained waste PCB, only a small number of particles can be prepared for analysis, which may affect the reproducibility of the data. One advantage, though, is that the automated SEM-EDS analysis can also determine the

degree of liberation of the metal phase of interest. Liberation is effectively whether or not a metal occurs in a particle only composed of that metal, or whether the metal is present as part of a multi-component particle, where for example only 50 percent of the area of the particle may be composed of the metal of interest. Usually, as the material is reduced in particle size, liberation will improve, but because of the energy needed for grinding, it is important to determine at what grind size the majority of the metal will be liberated from the component particles (Fig. 9). Similarly, over-grinding can alter the surface properties and hence influence recovery characteristics.

An alternative analytical approach is to use micro-X Ray Fluorescence (XRF) to provide elemental mapping and quantification along with particle classification and quantification. There are several significant advantages to micro-XRF. First, samples do not require any prior preparation, as either whole or crushed printed circuit boards can be spread out as a layer and then measured directly (Fig. 10). Whilst both manual and automated SEM-EDS are fundamentally surface analyses (the beam only interacts with at most a few microns of the surface being analysed), micro-XRF analysis is not purely a mode of surface analysis as, depending on the specific element, the detected energy line and the host material, the measured signal may be generated at depth within the host material. For example, Au may be detected at a depth of up to 3 mm within a host plastic. This can be advantageous in layered and laminated materials where the metals of interest may be 'buried' within the sample. In addition, depending on the area measured and the resolution used, a sample measuring 10 × 8 cm can be analysed in less than 16 min. The rapid analysis time and ability to measure unprepared samples may allow this technology to be used to screen materials on-line within a commercial sorting facility.

Fig. 9. Automated SEM-EDS (AMICS) particle images of printed circuit board samples showing particles mapped based on their chemical composition; bright orange is copper metal. Note that with the reduction in size from Sample A to Sample B there is increased liberation of particles solely composed of copper.



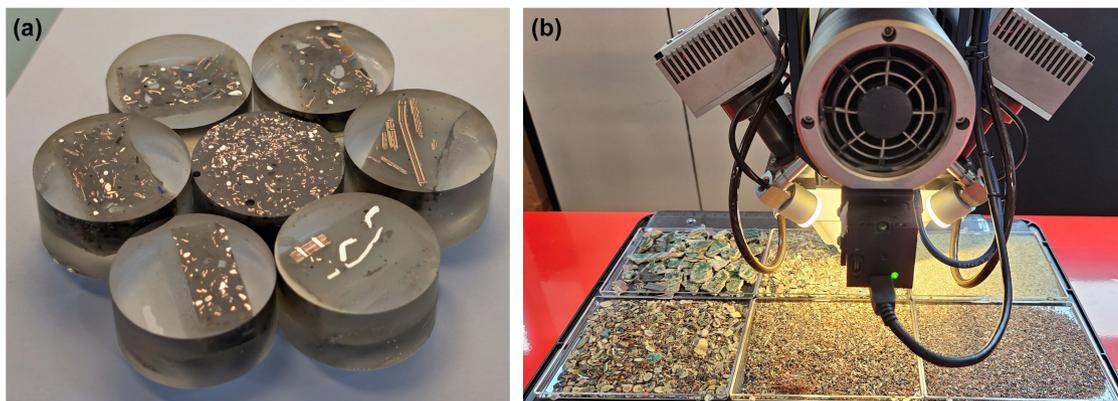


Fig. 10. (a) For automated SEM-EDS (AMICS) or manual SEM analysis, polished samples can be prepared in 30 mm diameter resin blocks; note the highly reflective Cu metal particles. However, a limitation is that only a small number of particles can be mounted in each block. In contrast, (b) using the Bruker M6 Jetstream scanning micro-XRF, no sample preparation is required and analysis is carried out open to air. Here, six waste PCB samples are dispersed as thin layers in 10×8 cm trays and measured directly.

Micro-XRF mapping can provide a clear visual representation of the distribution of key elements (e.g. gold), highlighting which particle types in 3D the elements deport to. As examples, such an approach can be applied to waste electronic goods prior to being dismantled for recycling. Fig. 11 shows several of the main electronic components within a dismantled tablet computer, in which micro-XRF mapping clearly highlights the elemental distribution within these components. Similarly, Fig. 12 shows a complete printed circuit board, in which micro-XRF mapping reveals the distribution of the main metal compo-

nents. During recycling, micro-XRF can be used as a rapid screening tool, perhaps during the initial trading of E-waste, assessing whether or not key payable, or penalty, elements are present within a sample of printed circuit board waste, and highlighting which particles the elements of interest occur in. Such an approach may enable particles containing an element of interest to be pre-concentrated as an initial stage in the reprocessing circuit. Fig. 13 illustrates this approach for a sample of coarse grained, shredded printed circuit board. The ‘full intensity’ map is based on the complete range of elements present and

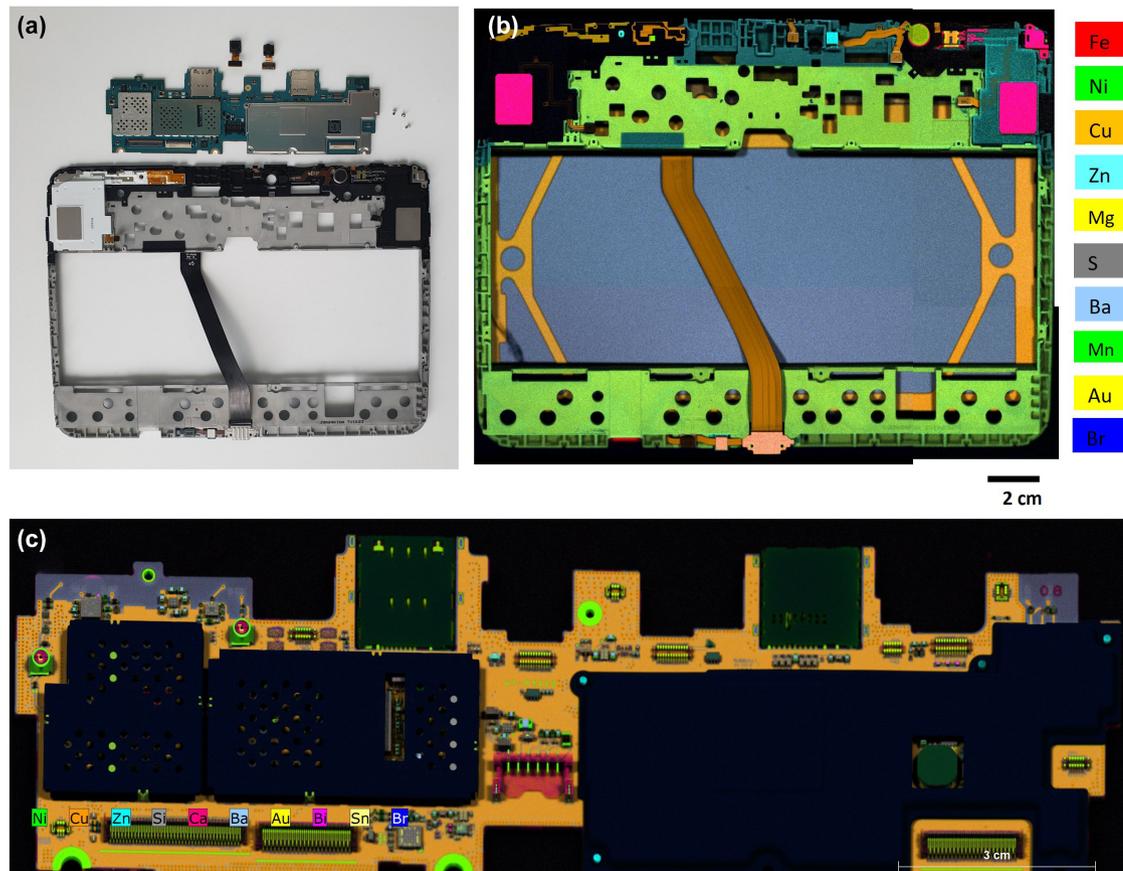


Fig. 11. Micro-XRF element mapping of a dismantled computer tablet, highlighting the distribution of metal elements to the different components.

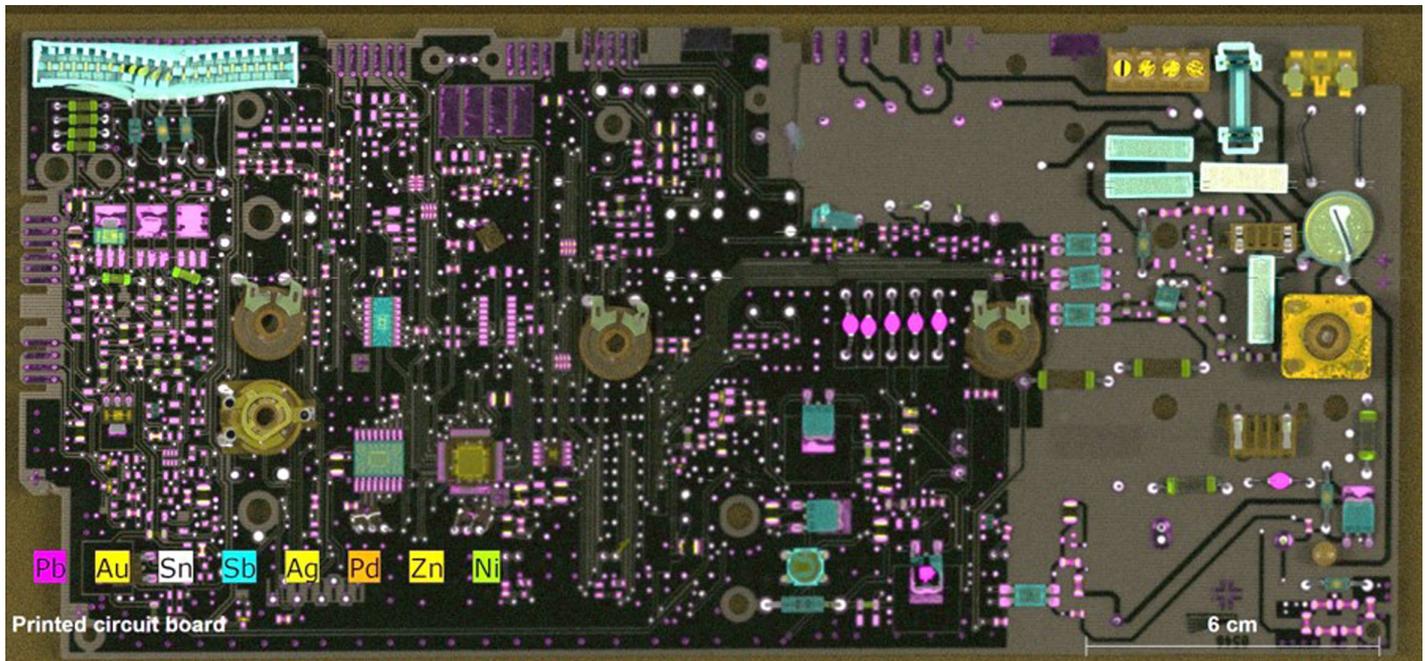


Fig. 12. Micro-XRF element mapping of an intact printed circuit board, showing the distribution of key metals within the electronic waste.

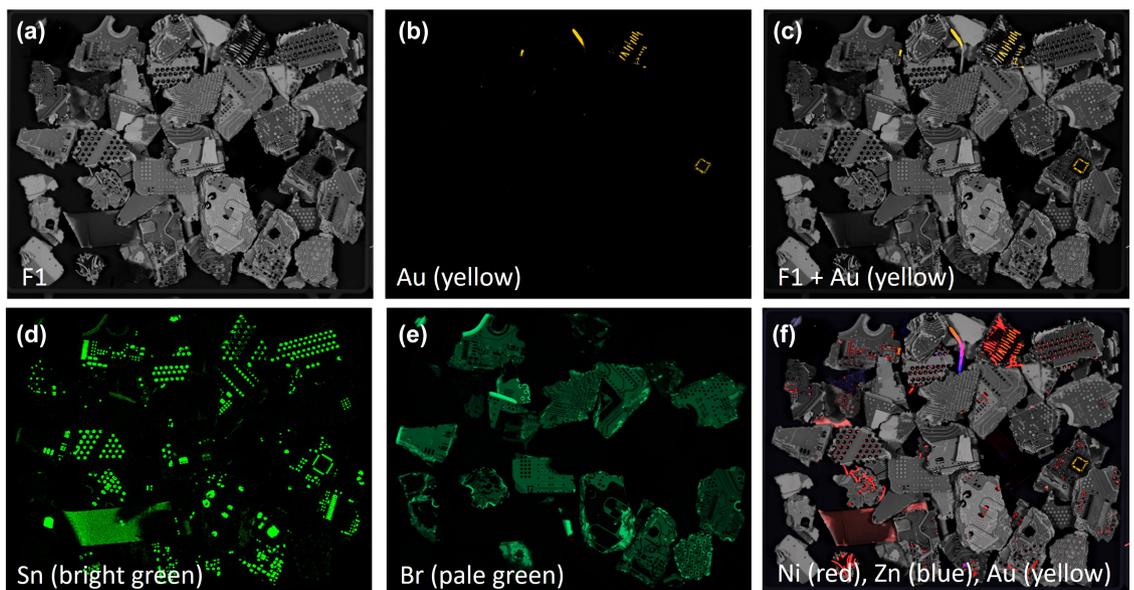
effectively provides an image of the scanned particles. These data can then be used to highlight the distribution of a single element, or a combination of elements. As noted above, depending upon the measurement parameters, the imaged gold may be at a depth of up to 3 mm within a host plastic particle. These images are qualitative and the 'brightness' is effectively based on the relative abundance of the element present, yet if a known standard was also analysed, then the elemental data could also be quantified. The AMICS software suite used in the automated SEM-EDS particle analysis can also be combined with the micro-XRF so that a large area sample could also be quantitatively mapped

in terms of the different types, and relative abundance, of particles present.

Discussion

Technological developments and global consumerism mean that there is a growing demand for metals. In addition, as new technologies are developed, the raw materials needed will also evolve to supply that need. Nearly all mineral deposits form over geological timescales, far in excess of our rate of mining; hence, the supply of raw materials is finite. This has led to the exploitation of previously uneconomic

Fig. 13. Micro-XRF mapping allows element distributions to be mapped in shredded printed circuit boards. (a) F1 full intensity (all elements) providing an image of the coarsely crushed PCB sample. (b) Same area, highlighting the distribution of gold (Au). (c) Gold element map superimposed on the F1 image highlighting the gold particle deployment. (d) Element map (same area) showing tin (Sn) distribution. (e) Bromine (Br) element map—the bromine is present within the printed circuit board plastics. (f) Multiple elements can be displayed together; here the image shows nickel (Ni), zinc (Zn) and gold (Au) superimposed on the F1 image.



deposits and also increased interest in the potential of mining frontier areas, whether the deep sea or in space. At the same time, the volume of wastes from sources such as LIBs and personal electronic goods is also increasing hugely. At present, these materials are viewed as, and treated as waste, rather than being considered as a human-derived multi-component commodity, despite the fact that they often contain valuable elements at concentrations far greater than occurring in natural ore deposits ahead of processing. Recently, China has reclassified black mass from being a waste to a commodity, providing that it meets a strict specification. In the global mining industry, advanced mineralogical and geochemical analytical techniques are routinely used to determine the optimum process to recover the mineral or element of interest. These same methods can be used to characterize waste streams, and thus help inform the most cost-effective and efficient way to recover the elements present within this waste and minimize losses to landfill. In this way, as before, there is money in waste and whilst unlikely to replace the need for mining of primary ores, recycling may be of growing significance in future.

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Suggestions for further reading

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