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Electro dynamic fragmentation of printed wiring boards as a preparation tool for their recycling

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ABSTRACT

The use of Electro Dynamic Fragmentation (EDF) enables selective fragmentation of materials through generating electrical discharges as a means of fracturing. Liberated materials can be thus processed downstream in a more efficient way especially when value-added End-of-Life (EoL) electronic equipment is recycled. The aim of this study was to assess the benefits of the EDF technology towards processing of EoL printed wiring boards (PWBs) in view their recyclability. Printed wiring boards were comminuted using EDF at three different settings and with a hammer mill for comparative experiment. The products coming out were characterized by optical microscopy, SEM and liberation oriented leaching. Subsamples from the various EDF stages were inspected to investigate the progress of cracks and degree of copper layers exposure. The different energy levels used during the EDF processing have resulted in different degrees of PWBs damages, starting from components removal to entire structure perturbation and size reduction. EDF has resulted in generation of a lesser amount of fines, however the optimal approach in view energy efficient post-processing of the studied PWBs was the combination between single-stage EDF for components removal only with subsequent shredding of the depopulated boards.

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1. Introduction

Recent statistics indicate that within the EU, only for the year of 2012, 9.1 million tonnes of electric and electronic equipment (EEE) were put on the market, while 3.5 million tonnes of waste EEE (WEEE) were collected and processed. Similar figures are reported for 2013 with 3.6 million tonnes of WEEE being treated. Out of this amount, about 2.4 million tonnes were recycled with objective of material valorisation and 0.2 million tonnes were used for energy production (Eurostat, 2016). WEEE usually contain non negligible amounts of different base and precious metals (up to 61%), and polymers (up to 21%) which renders them attractive as secondary resources compared to the primary mineral based ones (Tuncuk et al., 2012).

Various recycling technologies exist to process End-of-Life (EoL) printed wiring boards (PWBs), like for example direct treatment (i.e. without size reduction and removal of attached components) which targets both copper and precious metals recovery. In this case, the initial pyrometallurgical step is generally followed by subsequent hydrometallurgical and electrometallurgical opera-

tions. During pyrometallurgical treatment, the polymers, which form integral part of the PWBs, are used both as reduction agent as well as energy source due to their intrinsic calorific value. Nevertheless, pyrometallurgical operations require extensive off-gas cleaning systems to prevent emission of hazardous substances to the environment. The smelting step results in a precious metals rich copper mate phase and a lead slag. Following this step, hydro- and electrometallurgy are employed to recover copper through electrowinning and precious metals are subsequently refined (Schluep et al., 2009).

Hagelüken (2006a) mentions that the interaction between smelting installations and dedicated pre-processing and sorting plants should be considered with care as they both could benefit from mutual optimisation. The same study suggests that there is a room for improvement in this direction and points out that the recovery rate of a given element from an input stream is inversely proportional to its concentration in the output fraction. This highlights the potential for ever more selective fragmentation techniques. Parallel to pyrometallurgical processes description, many papers have referred to development of hydrometallurgical techniques for PWBs recycling. Notwithstanding, Schluep et al. (2009) mention that in contrast to pyrometallurgy which has proven track records, there is no sufficient data available in the public domain to

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conduct an independent review of a hydrometallurgical process for recycling of PWBs in order to prove its efficiency, sustainability and environmental performance. Nevertheless, toxic fumes generation and high investment and operating cost still remain as drawbacks for the pyrometallurgical option. Schluep et al. (2009) further add that it would be possible to treat complex wastes such as copper and precious metals bearing PWBs in classical smelters in China or elsewhere, but the installation of an off-gas treating systems as well as the highly sophisticated operation of these smelters would be expensive and more difficult to step up. It is shown that although traditional process routes possess their proven niches, trying new techniques and possibilities as a way to further process improvement is to be equally encouraged (Reuter et al., 2013).

In a recent scoping study primitive methods for PWBs recycling are mentioned to be used in some workshops in China (Guo et al., 2009). These techniques include open-air burning and acid washing of PWBs and provoke organic compounds release into environment. In particular, polybrominated diphenyl ethers (PBDEs) which are commonly referred to as brominated flame retardants, are emitted. In contrast, within the EU, WEEE streams and their processing are regulated through legislative acts such as the WEEE and RoHS directives (Tuncuk et al., 2012). The WEEE directive for instance, discusses reuse and recycling of WEEE with the objectives of reducing the ultimate amount of waste disposed and improving the environmental aspects around WEEE processing (Eurostat, 2016).

Whatever the processing method for WEEE, apart from environmental issues, the economic incentive is a factor of important consideration. The concentration of base and precious metals being the main materials targeted has to be taken into account accordingly in view of process selection and dimensioning. Hagelüken (2006a) mentions three grade categories for e-wastes based on their gold content. Low grade: with concentration below 100 ppm (e.g. TV-boards); medium grade comprising between 100 and 400 ppm (PC-boards, laptop-computers, some mobile phones) and high grade - above 400 ppm (e.g. some mobile phones, ICs, MLCCs). Whilst various studies dealing with the average metal grades in PWBs exist, Tuncuk et al. (2012) citing Hagelüken (2006b) report that for PC derived PWBs one can expect the following concentrations: Cu 20%, Au 250 ppm, Ag 1000 ppm and Pd 110 ppm. It is logical to assume that these metals are somehow repartitioned between the boards and the components on them. In a way to ease PWBs processing it might prove therefore feasible to separate components and depopulated boards into two individual streams, with each of them to be treated in a dedicated manner. In that context, Wang et al. (2016) have described various methods of removing the components from waste PWBs however the use of EDF for this purpose has been virtually not reported. From other hand, only few studies have appeared so far dealing with high-voltage comminution of entire WEEE (Duan et al., 2015; Zhao et al., 2015).

The EDF technology has attracted several studies during the recent years, among them (Wang et al., 2011), (Shi et al., 2013) and (Razavian et al., 2014) have investigated its use as a pre-weakening tool for mineral ores. This interest was provoked mainly due to the inherent fragmentation principle which differs radically from the breakage mechanism of traditional crushers. EDF does not blindly fragment the material, but induces fractures according to the intrinsic properties of the material, in particular the contrast between dielectric constant of the different phases (SELFRAG communication, 2016). In further studies, Wang et al. (2012) have compared the mineral liberation achieved by EDF and traditional comminution at identical specific energy inputs. Van der Wielen (2013) has extensively compared the EDF impacts on various rock types. These experimental works have been based on the use of the SELFRAG Lab system, which is a batch one. Recent

research however has been conducted towards setting up continuous equipment, for instance fragmentation of mineral ore has been studied in pilot scale continuous EDF equipment (Zuo et al., 2015).

Whilst most of the EDF application research done by far was focused on mineral ores, the EDF technology has a chance to penetrate into circular economy concept notably within high value materials recycling like for example carbon fibres (Roux et al., 2014). It is worth to mention that EDF-based bottom ash treatment plants and silicium rod crushing plants are currently being installed by the SELFRAG AG.

With the above mentioned on the background, the current work places a particular emphasis upon the pre-treatment of PWBs with an EDF technology using a SELFRAG Lab system. A secondary objective was to try to compare the SELFRAG system with a traditional shredding equipment in terms of resulting structure of the material and whenever possible energy consumption. The latter however appears quite tricky in practice, since energy in shredding depends on many factors such as output size, dimension and throughput of the shredder used (in our case hammer mill), filling degree of the chamber and others. From other hand, during EDF, output results are directly dependent on the amount of energy dissipated through the sample controlled via operating parameters such as voltage, frequency, and number of applied pulses. Moreover, the EDF equipment used in this study is a Selfrag Lab batch mode unit and as such is less energy efficient than a continuous machine. The same however is valid for the comparative unit used, being a semi-batch mode laboratory scale hammer mill. Another aim of the work was to develop and verify a methodology for tracing the liberation of the copper foils from PWBs during EDF processing and to compare its liberation degree with the one of a traditional shredder. Given the specific resulting impacts from the EDF, it is tangible to anticipate effects such as PWB depopulation and delamination.

2. Materials and methods

Representative PWB samples have been provided by the project partner Immark AG, Switzerland. Initial exploratory tests have been conducted using randomly picked PWBs originating from obsolete computers, with more detailed experimental work being performed on identical motherboards delivered by Immark AG.

A combination hammer-knife mill manufactured by Laarmann (the Netherlands) has been used as comparative grinding device. It is a custom-developed mill based on a CM4000 platform having the possibility to switch between knifes and hammers fixed onto rotating head. A 10 mm screen is placed inside the grinding chamber so that ground material granulometry is always below 10 mm. Depending on the mode (knifes or hammers), the maximum power output varies between 5.5 and 8.8 kW. Rotation speed is adjustable as well, and in this study has been set to 1025 rpm. The gap between the hammers and the fixed plates has been set to 3.5 mm.

A major challenge when designing process flow sheet for PWBs is the sample representativeness. Samples which appear similar may still be very different one from another in terms of chemical composition. Therefore, one needs to be careful with results interpretation in terms of material balancing and rather focus on behavioural trends, especially when performing laboratory scale research. This is due to the extreme heterogeneity of e-waste streams, best represented by the PWBs entering recycling plants. In this study, identical entire motherboards have been water-jet cut always under same procedure to fragments of 4 × 4 cm and divided into three groups. In a next step, they have been depopulated either by SELFRAG lab system (i.e. at Stage 1 as explained fur-

ther) or manually, the latter intended to serve as comparison during the liberation oriented leaching. The depopulated fractions have been further processed through EDF or hammer mill.

Particle size distribution curves of the PWBs following the various fragmentation tests have been constructed after dry sieving using a set of laboratory sieves with the following openings (mm): 20; 12.5; 8; 4; 2; 1; 0.5 and 0.212. It should be noted that due to the irregular shape of the comminuted PWBs, granulometric results are used merely as a means to compare size population trends and to a lesser extent as an estimate of the real size of the fragments.

Liberation-oriented leaching experiments have been realized with the aim to estimate the degree of a physically liberated copper being directly accessible to a nitric acid leaching solution and thus to enable comparison between the different treatment operations. Therefore leaching has been performed on depopulated PWBs only and on such derived from Stage 2 EDF and hammer milling. The leaching has been realized inside a 1.0 L double wall top-agitated reactor at 10% solid density, temperature of 30 °C and nitric acid concentration of 3 M. The latter was chosen to be in excess of the stoichiometrically required concentration needed to bring the entire copper in solution from a PWB with 24% concentration of copper. More precisely, the stoichiometrically required concentration was doubled and rounded up to 3 M. Samples from the leaching reactor have been taken after 20, 40, 60, 90 min and further at 2, 4, 6, 24, and 26 h. Through direct estimation of the copper brought in solution in comparison to the total available copper, the degree of copper liberation as function of the various processing steps could be determined with sufficient level of accuracy (metal liberation proxy).

Base metals content in the depopulated PWBs has been determined by ICP-AES (Varian, Liberty II) following sample digestion (100 g) in triplicate with nitric acid and final aqua regia digestion with the respective dilution in volumetric flasks. The mean chemical analysis has indicated that the major base metals account for approximately 25% of sample mass, with 24% being Cu and the rest repartitioned between Ni – 0.4%, Pb – 0.2%, Zn – 0.3% and Sn – 0.2%. Fe content was measured as 0.3%. Liquid samples were assayed for copper by AAS spectroscopy (Analytic Jena CONTRAA 300).

Samples taken before and after fragmentation and during leaching were prepared as polished sections and inspected by optical and scanning electron microscopy. Optical observation was carried out by the use of an Olympus BX60 microscope. Polished sections were prepared using a Struers LaboPol-35 polishing machine. SEM observations were carried out by the use of backscattered electron (BSE) detectors on polished sections using a FEI ESEM-FEG XL-30 system working in low vacuum mode and at 30 kV of accelerating voltage. The ESEM was coupled with an EDAX energy dispersive X-ray spectrometer (EDS) for elemental microanalysis and with a sapphire super-ultrathin window for detection of light elements.

2.1. Energy consumption estimation

2.1.1. Electro dynamic fragmentation

The energy input transmitted into the target material cannot be measured directly. Therefore an approximation is calculated based on the generators energy expenditure, the allied voltage and the number of successfully applied pulses. Selfrag Lab utilizes Marx generators containing four condensers each with a capacity of 150 nano Farad (nF). The condensers are serial-connected which allows calculating a total capacity of C = 150 nF/4 = 37.5 nF. As a rule, lab machine based on such generators is calculated using Eqs. (1) and (2) below (SELFRAG personal communication). For the sake of clarification, both energy input per pulse and total energy input per treatment are indicated.

Energy input per pulse is:

$$E = 1/2 * C * U \wedge 2 \tag{1}$$

and energy input per treatment respectively,

$$E = 1/2 * C * U \wedge 2 * n \tag{2}$$

where

- E - energy (J)
- E - energy (Wh). Energy in Watt-hours corresponds to Joules divided by 3600 s.
- C – capacitance (nF)
- U - operating voltage (kV)
- n - number of pulses.

Using Eq. (1), the energy input per pulse at a characteristic voltage of 150 kV is calculated approximately as:

$$E = 1/2 * 37.5 \text{ nF} * (150 \text{ kV})^2 = 421 \text{ J} = 0.117 \text{ Wh} \tag{3}$$

The operational parameters reported above could be adjusted based on experience and plant specification available at SELFRAG AG. The available voltage range finally depends on the installed capacitors, likewise on the frequency. For example, if less capacitance is installed, less energy/pulse is transported and frequency can be increased. The shape of the vessel is also a factor of consideration when energy expenditure is an issue. Due to the exploratory character of the performed study, a standard generically designed vessel was used, which as a rule is suitable for bulk materials and not for specific shaped PWBs. The idea is that all bulk material progressively passes and leaves the impact zone via a screen placed at the vessel bottom, which is not the case of PWBs due to their unique shape. Moreover in a batch closed bottom setup, the energy dissipation can be non-uniform which increases overall energy consumption.

2.1.2. Hammer mill

The energy consumption during the shredding with the Laarmann hammer mill has been recorded by means of a Fluke 434 Series II Energy Analyzer. The device has been connected with its dedicated probes on each phase of the three-phase power cable linking the main electrical socket and the mill. The data recorded by the device refer to net power values, expressed in W. The minimum, maximum and average values were given by the device for each second. The data has been transferred towards a PC by means of an optical cable connected to an USB port using the dedicated FlukeView software accompanying the unit.

As mentioned, the hammer mill shredding of the PWB has been realized for comparative to Selfrag Lab purposes. Therefore, only about 150 g has been ground at each batch run, being the minimal weight which the mill could handle as input. From other hand, this amount has been considered as an optimal one for the subsequent analytical leaching, done on a representative sample taken by a riffle sampler. The shredder has been fitted with 10 mm bottom sieve meaning that the output sample was always below 10 mm. Nevertheless, some particles larger than 10 mm could stay stuck inside the shredding chamber and at the same time, given their shape, other particles could pass through the sieve if at least one of their dimensions is smaller than 10 mm.

In order to evaluate the energy consumption of the hammer mill, an identical sample to the one fragmented by Selfrag has been shredded at a rotation speed of 1025 rpm. The average power registered at each second and recorded by the measuring device has been plotted against time, resulting in obtaining a power signature over time which includes also the "idle" power intake. When the shredding process is finished, the actual energy consumption is estimated by integrating the recorded power sequences over time,

the "idle" power consumption not being taken into account. The specific energy is then calculated by dividing the total energy consumption by the weight of the sample. In the tested case and under the above described operational conditions, the specific energy consumption for the shredding has been calculated as 23 kWh/t considering a cycle with a duration of 119 s.

2.2. EDF pre-processing parameters

Initial investigations have been aimed at delineating the visible effects experienced by the PWBs when subjected to the three EDF stages performed at various levels of energy and intensity. The first stage was intended for components removal (PWB depopulation), the second stage has aimed structure delamination inside the depopulated boards and the third stage has targeted an entire destruction of the compounded material of the depopulated PWB and their size reduction.

Stage 1 EDF processing has been always fed with 12 fragments of intact water-jet cut PWB each of 4 × 4 cm. For Stages 2 and 3 the equipment vessel has been fed again with twelve and fifteen 4 × 4 cm fragments respectively, which have been depopulated during Stage 1.

For Stage 1, the equipment has been run at 150 kV voltage, 5 Hz frequency and 40 mm electrode gap. The number of pulses was adjusted as to achieve maximum degree of components removal from the PWB. Depopulation has been considered to be completed when first delamination of copper foils started to occur. In practice, the processing was done by applying successive amounts of pulses, with samples being visually observed after each batch and delamination effects inspected. Fifteen depopulation tests on identical boards have been performed. To estimate the energy consumption, the above mentioned parameters and Eq. (1) were used. The average energy consumed during these 15 tests is calculated as 132 kWh/t. This energy consumption values should also be taken as first benchmark indication for a batch process performed under laboratory conditions. As with the hammer mill operation, it can be assumed that energy consumption of a continuous EDF process would fall below these values.

Stage 2 investigations were performed at 170 kV or 180 kV voltage, 5 Hz frequency and 40 mm electrode gap respectively. Similarly to Stage 1, successive pulse "shots" were applied and samples inspected visually after each one. The number of pulses has been recorded as reference and used further to always reproduce Stage 2 operational and set-up conditions. To realise this, precise number of pulses were introduced until the same reference energy level was reached. The average calculated energy has been 877 kWh/t.

Stage 3 fragmentation has been realized on depopulated boards from Stage 1. The working parameters have been kept the same as those used at Stage 2, however higher number of pulses was applied resulting finally in PWB being reduced in size. The average energy for this stage has been calculated as 1485 kWh/t.

To sum up, the increased number of EDF pulses, with rest operating parameters kept constant has resulted in immediate components removal, i.e. depopulation. Then, when the depopulated boards are impacted through further pulses, the inner layers of the boards start to delaminate. Provided that after this step the number of pulses is further increased, the boards start to fragment having their size reduced. In that context, Stage 2 could offer an ideal compromise between energy consumption and resulting delamination effects bringing an optimal liberation of copper foils and threads without excessively reducing the size of the fragments.

3. Results and discussions

Fig. 1 presents cross sectional view of an intact PWB before being subjected to fragmentation impacts. The appearance of four
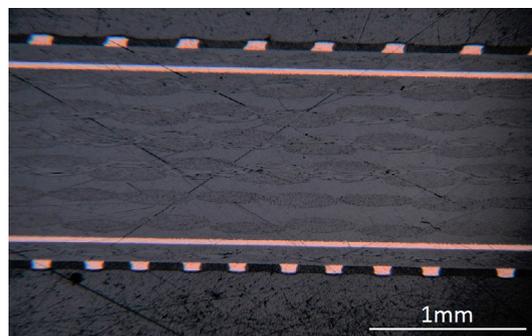

Fig. 1. Cross-section of intact PWB.

copper layers could be gladly distinguished with two of them positioned onto each side of a glass fibre reinforced polymer matrix.

3.1. Particle size analysis

The particle size distribution curves for the depopulated samples subjected to hammer milling and for those coming after EDF Stages 2 and 3 are shown in Fig. 2. A perusal of the curves indicates that the mean sizes of the hammer mill ground PWBs and of those coming after Stage 3 EDF are nearly identical. Hammer mill ground material is entirely below 10 mm due to the bottom sieve fitted inside the grinding chamber. PWBs treated after Stage 2 possess larger amount of coarser fractions in comparison to those processed at Stage 3. It should be noted that for the finer size classes (i.e. below 3 mm), particle size curves for PWBs treated through EDF Stage 3 and through hammer mill do follow very similar trend, although mean particle size is different. That is a general feature of the EDF technology being also observed during mining and other exploration-oriented projects. As discussed in the previous section, one possible reason lies in the highly random and irregular shape of the ground PWBs. It is not to exclude that needle-shaped particle, for example liberated glass fibres of ca. 10 μm in diameter or metallic pins do report in lower size fractions due to their small one side dimension enabling passing through the opening of a sieve, whereas their longer dimension would not. It should be nevertheless noted that the traditional grinding using hammer mill brought the highest yield of fine fractions, which confirms the fact that the EDF produces less fine material.

3.2. Liberation oriented leaching

The results from the liberation-oriented leaching are summarized in graphical form in Fig. 3. An immediate impression is the existence of two different leaching patterns. PWBs submitted to depopulation only, show marginally lower copper leaching degree. Here it is interesting to note that boards depopulated either manually or through EDF show no distinctive behaviour in terms of copper being brought into solution. It could be thus concluded that regardless of the depopulation mode, the fact that components are removed contributes to a very limited liberation of the internal copper layers. We could assume that the degree of copper brought into solution in the first 5–6 h correlates well with the degree of physical exposure of copper (liberation degree). This observation confirms, similarly to the particle size distribution curves, that Stage 1 EDF treatment brings components removal, whilst preserving the internal board structure intact. Copper leaching kinetics for depopulated boards is much slower than the one for the fragmented samples with the two curves tending to flatten only after 24 h. For PWBs being treated at Stage 2 EDF or those being hammer milled after Stage 1, the curves virtually overlap showing that the
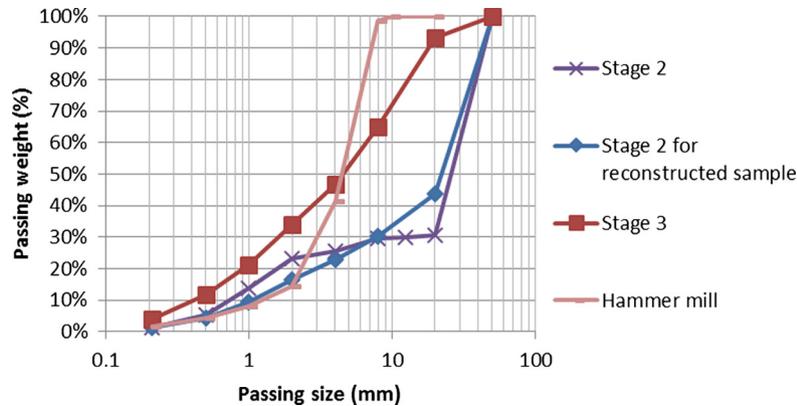
Fig. 2. Particle size distribution of PWB following EDF Stages 2 and 3 and hammer milling.
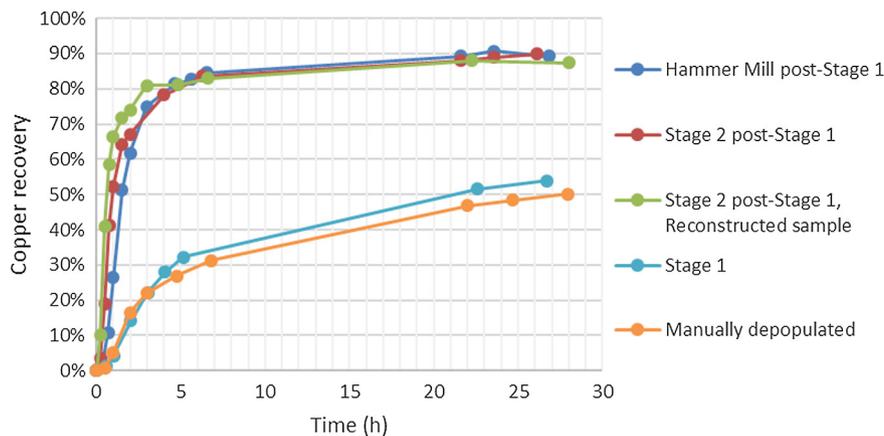

Fig. 3. Percentage of leached copper as function of depopulation mode and fragmentation sequences used.

majority of copper is leached within about 5 h. Following that period, curves begin to flatten with the percentage of leached Cu after 7 h reaching around 80%. Between 7 and 24 h leaching, no significant additional recovery of copper can be observed. It should be noted that processed samples at Stage 2 entail large number of 4 × 4 cm fragments, i.e. PWBs have not been fragmented, but rather delaminated. This brings the assumption that the EDF was capable of achieving similar liberation results to the hammer mill, but at much coarser mean particle size without the necessity to finely ground the material below 10 mm. An added benefit here is the lack of shredder dusts, which are notorious for their contribution in metal losses.

The implication of the liberation oriented leaching is that the EDF treatment could operate as a first early stage separation leading to components removal and concentration of certain metals in depopulated PWBs while others reporting in the components. The depopulated PWB could be further reduced in size via hammer mill to render copper available to hydrometallurgical downstream processing.

3.3. Observations of processed PWB

Fig. 4 presents two optical views of identical input PWB samples depopulated through EDF Stage 1 and processed further. The sample on the left has been subjected to EDF Stage 2 step, while the sample on the right has been hammer milled. The traces left by the both impacts are quite visible. For the Selfrag treatment (left), the delamination is evidenced by an intact glass fibre reinforced polymer backbone and by negligible size reduction effects,

while hammer mill does not provoke delamination (right). Hammer milled material has eventually witnessed minor delamination effects, which most likely originate from the Stage 1 depopulation step.

Fig. 5 left shows a cross-section image of a randomly chosen boards treated at Stage 2 followed by a nitric acid leaching (sample taken after 6 h). One could note that due to structure opening the leaching front is progressing in direction of the metal surface exposed to the leaching solution. As indicated in Fig. 1, it is common that intact PWBs possess superficial layer of copper threads. In Fig. 5 right, the image suggests that most likely the superficial layer has already been stripped off during the EDF processing, with the remaining of the copper starting to be attacked by the acid as indicated by the neat surface. The same image shows leaching front advancing with coroded and dented edges appearing as well. It could be clearly seen how the leaching solution has uniformly attacked the edges of the coper foil, implying liberation of polymer-metal boundaries due to PWB structure opening. The initial crack network of the PWB comminuted by EDF appeared to increase during the agitative leaching due to attrition effects, as leaching accelerates acid diffusion towards the copper surface ultimately resulting in more metal extraction after about 5 h (Fig. 3).

Since the inner structures of the PWBs have been damaged after the EDF treatment, after having reacted with the nitric acid some residual metals could be displaced from their original positions or transform as precipitates. Therefore in Fig. 6 (right), residual metals can be seen in vicinity of the edges of the openings (pale colored, as a lighter color in BSE imaging indicates a higher average atomic number). The remaining after leaching copper foil seen in
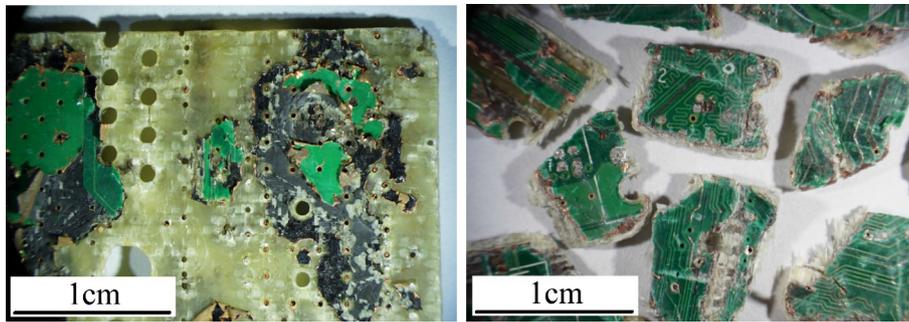
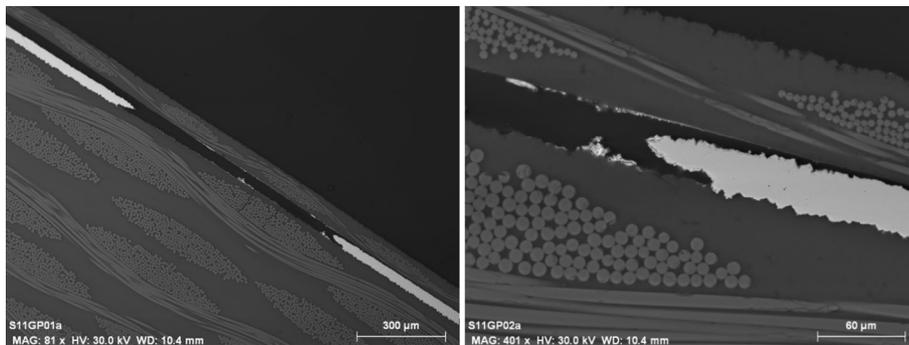**Fig. 4.** Fractions of fragmented PWBs after EDF Stage 2 (left) and hammer mill (right).

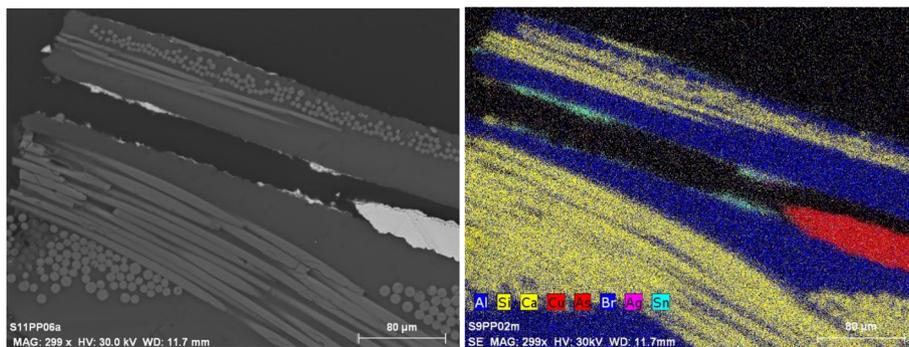**Fig. 5.** Cu foil being leached (left), with zoom at the leaching spot (right).

Fig. 6. SEM-BSE of selected spot in leached PWB (left) with EDS super imposed false colours (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
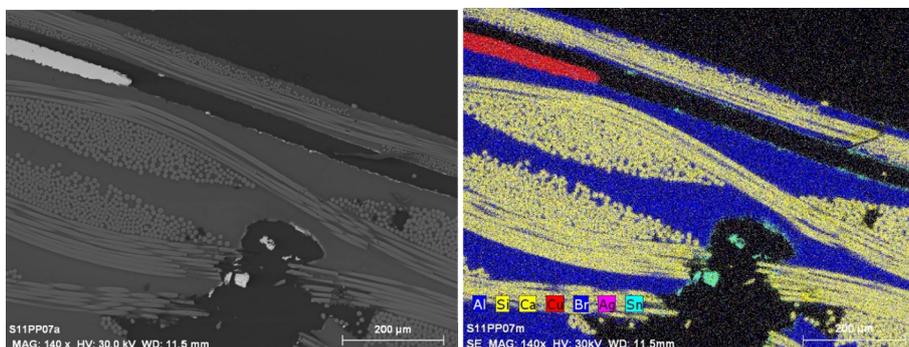

Fig. 7. SEM-BSE of selected spot in leached PWB (left) with EDS super imposed false colours (right).

Fig. 6 left is clearly detected and evidenced in red (Fig. 6 right). Fig. 7 illustrates another cross-sectional spot of a PWB coming from Stage 2 EDF, being subsequently leached for 6 h. The edges at the openings contain residual metals which are most likely tin oxide precipitates with minor silver content. Tin precipitation has been suspected and visually observed during the leaching tests,

which corroborates well with the results shown in Figs. 6 and 7. One possible source of silver are the solder materials which are usually tin-based, but recently having been prepared with Ag-containing alloys (Hurtony et al., 2016). In yellow, one could clearly distinguish a glass fibre weave. The blue color indicates bromium used as flame retardant in plastics. It should be noted, that although the image announces aluminium in blue, this color should be attributed to bromium. The EDS system registers bromium but falsly indicates aluminium since the first spectral peak of aluminium coincides with that of bromium. Therefore the software will automatically attribute the signal to aluminium even though it is actually bromium. This situation has been cross-checked through SEM-EDS analyses.

4. Conclusions

In this study Electro Dynamic Fragmentation realized through a SELFRAG system was investigated as a way to induce down-stream relevant effects in view recycling of end-of-life (EoL) printed wiring boards (PWBs).

The application of the EDF at various operational parameters and modes has resulted in different levels of PWB damage; from components removal to structure opening and size reduction. The different EDF effects influencing also the final copper liberation degree are linked to varying energy inputs. Due to the lab scale batch mode being tested, the obtained energy consumption data and trends should be used as indicative information only. Lower energy consumption however is recorded in recent SELFRAG continuous processing mode trials.

The intrinsic breakage principle of the EDF technology enables to guide or direct energy only where wanted, with the mechanical damages of resulting shock wave/impact energy at high velocity being a guarantee for the selectiveness of the process. This unique principle could be the principal reason for the changes inside the internal structures observed at the various tests. The most fundamentally important aspect of the EDF is structure opening along interfaces which enables metals leaching from PWBs at relatively coarse size ranges.

If the ultimate objective of particular project is downstream copper removal from depopulated PWBs by hydrometallurgy, we infer that similar liberation degrees could be achieved by either hammer milling or EDF Stage 2. From energy perspective however, the first option is to be preferred. Nevertheless, particle sizes and textural characteristics of the output products are quite different after hammer milling and EDF Stage 2, which has to be considered as well. It is to note that any eventual hydrometallurgical step will be facilitated since the majority of ferrous metals and plastics embedded inside the components are removed in advance.

Another practical implication of the results is that through the use of EDF-SELFRAG, PWBs could be stripped out from their components. The two fluxes thus obtained could be separated and directed towards dedicated downstream processing since base, platinum group metals and precious metals tend to be repartitioned (results not reported here). In such a way the SELFRAG system could allow an elegant means of depopulation while minimizing metal losses in the remaining depopulated boards.

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