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The influence of printed electronics on the recyclability of paper: A case study for smart envelopes in courier and postal services

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ABSTRACT

The aim of this paper is to analyse the effects of the presence of printed electronics on the paper waste streams and specifically on paper recyclability. The analysis is based on a case study focussed on envelopes for postal and courier services provided with these intelligent systems.

The smart printed envelope of the study includes a combination of both conventional (thin flexible batteries and resistors) and printed electronic components (conductive track layout based on nanosilver ink). For this purpose, a comparison between envelopes with and without these components (batteries, resistors and conductive track layouts) was carried out through pilot scale paper recycling tests. The generation of rejects during the recycling process as well as the final quality of the recycled paper (mechanical and optical properties) were tested and quantitatively evaluated.

The results show that resistors are retained during the screening process in the sieves and consequently they cannot end up in the final screened pulp. Therefore, mechanical and optical properties of the recycled paper are not affected. Nevertheless, inks from the conductive track layouts and batteries were partially dissolved in the process water. These substances were not totally retained in the sieving systems resulting in slight changes in the optical properties of the final recycled paper (variations are 7.2–7.5% in brightness, 8.5–10.7% in whiteness, 1.2–2.2% in L^* values, 3.3–3.5% in opacity and 16.1–27% in yellowness). These variations are not in ranges able to cause problems in current paper recycling processes and restrict the use of recycled paper in current applications. Moreover, real impacts on industrial recycling are expected to be even significantly lower since the proportion of paper product with printed circuits in the current paper waste streams are much lower than the ones tested in this work. However, it should be underlined the fact that this situation may change over the next years due to the future developments in printed electronics and the gradual penetration of these types of devices in the market.

1. Introduction

Printed electronics fabricated using a roll-to-roll (R2R) printing technique has drawn intensive attention from both research and industry in the past decade (Bollström et al., 2009; Tobjörk et al., 2008). This fact is mainly due to its great potential to inspire new products and applications (i.e. printed sensors, Radio-Frequency Identification (RFID) tags, integrated smart systems for consumer packaging) (OE-A, 2013). The competitive manufacturing costs and their flexibility in terms of production volumes, make them easier to adapt to fast changing markets (Kunnari et al., 2009). Moreover, they can be attached to flexible substrates (Colae, 2014).

With the aim of providing new solutions, the EU project ROPAS started in 2011. The main goal consists in developing wireless sensor devices for paper substrates, which can be manufactured using high-end and low-cost printing techniques. The product that is of interest to us is a smart envelope with a printed circuit which includes, sensors, batteries and a wireless communication chip integrated on paper substrate. This device enables tracking and tracing of the mail while it can also provide information regarding the opening status of the envelope (patent pending). More precisely a code is incorporated in each one of the smart envelopes so that it can be controlled if it has been opened by an authorised person. Encrypted code signal transmission is provided via internet, allowing logistics companies to track and trace at any time

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the location and opening status of the envelope. A commercial thin and flexible battery of 3V supplied by Enfucell Oy (2013) provides energy for data transmission. In case of unauthorised opening, information is reported to the logistics company. Therefore, this development is suitable for the delivery of confidential and personal documents like passports, visas, or mobile phone SIM cards.

As a result of these new functions and competitive manufacturing costs, an increasing use of this type of smart devices is expected in the near future (OE-A, 2013). Indeed, market analysts forecast that the product market value would rise to 44.25 billion US Dollar in 2021 (Das and Harrop, 2011). However, potential constraints related to the end of life of such devices should be considered before their launch onto the market. Due to the fact that such kind of smart devices are embedded in the non-ICT (Information and Communication Technologies) objects, they cannot be separated during the pre-treatment of waste (Wäger et al., 2005). In the case of the smart envelope, this device should be considered as a small, thin and flexible object embedded in a paper envelope. Therefore, for most users, it will be regarded as a paper product rather than an ICT product. The questions that arise therefore are, which is the most appropriate end-of-life treatment for these devices? and to what extend could these devices affect the recycling process and its products?

In the case of paper, the European List of Standard Grades of Recovered Paper and Board EN-643 (CEN, 2014) provides paper sector in Europe with clear guidelines and quality requirements for the recovered paper. However it does not provide guidelines or requirements with regard to the printed circuits. Moreover little is known about the efficiency of technologies and processes typically used by the paper recycling industry such as sorting, pulping, screening, flotation deinking and washing (Mckinney, 1995; Teschke and Demers, 2006) in eliminating substances contained in printed electronic circuits. In fact, according to the Technical Report CEN/TR 13688: 2008 on material recycling, plastic laminations, waxes and bitumen, which are substances that are contained in printed electronic circuits, are not compatible with current paper recycling technologies.

Within this context, Wäger et al. (2005) studied the effects of the use of RFID tags in retail sector. Results from paper recycling showed that the electronic components of the tags could enter the non-electronic waste streams and can cause a problem if the antenna is detached from its support. However, it was concluded that more research through on-site experiments in recycling plants was needed.

Consequently, the main goal of this study is to analyse the influence of printed electronics on paper recycling processes. The analyses are based on the first version of the smart envelope developed in ROPAS project. These novel smart envelopes (still under development at the time of preparation of this paper) combine conventional and printed electronic components (i.e. conductive track layout based on printed nanosilver ink) as fully printable devices are still not technically feasible due to signal transmission performance constraints. Additionally, it was decided to focus on the smart envelope components that could potentially have the highest influence on paper recycling (i.e. silicon-based resistor, battery and nanosilver conductive track layout) due to the high number of components in the smart envelope device.

Pilot scale experimental tests, based on industrial processes of pulping, screening and paper formation, were carried out on paper samples with and without these components. The comparative analyses were based on the amount and composition of the rejects generated as well as the measurement of the mechanical and optical properties of the final recycled paper.

Furthermore, a discussion is provided regarding the possibility of different components to pass through the sieves and end up in final recycled paper.

2. Materials and methods

2.1. Approach of recyclability assessment

To design the experimental recycling tests, a list of components of the first version of the smart envelopes developed within the ROPAS project was developed.

(1) *Battery*. Commercial thin and flexible battery based on zinc and manganese components. It provides the necessary power supply for the operation of the smart envelope.
(2) *Antenna*. It is a nanosilver-printed component that transmits wireless signals to a base station for the track and trace and the opening status of the envelope.
(3) *Sensor switch*. This is a numerical keyboard. It is meant to be used by the receiver. The receiver enters a unique code that ensures that the envelope has been received and opened by the correct person.
(4) *Signalling*. A silicon-based chip monitors the product status.
(5) *Fibre-based substrate*. It is used as a base material on which all the aforementioned components were integrated and connected with printed conductive tracks made from nanosilver ink.

Due to the large number of components, it was decided to focus on those that could potentially have the major influence on paper recycling (i.e. silicon-based resistor, battery and nanosilver conductive track layout).

(1) Silicon-based resistor. Due to its small size (1.6 mm × 0.8 mm × 0.5 mm), resistors could pass through the screening systems (sieves), end up in the recycled paper and therefore affect the paper quality. On the other hand, processing efficiency could be decreased in case that the resistors are retained by screens (Wäger et al., 2005). This is because retained components on the surface of the sieve reduce the pulp flow and thus the process yield is lower.
(2) Flexible and thin battery. Zinc and manganese components could end up in the final paper affecting final recycled paper quality.
(3) Design based on printed conductive tracks (layout). These are produced by a novel printing technology with nanosilver inks. The fate of the conductive inks during the recycling process is uncertain. Research is required to shed light on this issue.

2.2. Materials: paper and electronic components

Recycling tests were performed considering a set of envelopes with and without the three above-mentioned printed electronics components. Samples without components were considered as "blanks" for pilot tests and all the results were compared to them as a reference.

The envelope paper used in tests is LumiSilk from StoraEnso, which was used as a substrate for printed electronics. The selected components of electronic devices included a layout based on nanosilver printed conductive tracks (supplied by VTT, Finland), silicon-based resistors (SMD[1] 060312K 1%, Multicomp MC0063W0603112K) and batteries (SoftBattery®, Enfucell). These components were labelled as impurities for the comparisons to the control (blank). The composition of the printed electronics components in study is detailed in Table 1.

[1] SMD. Surface Mount Device.