Advanced Manufacturing of Flexible Electronic Circuits by Transfer Foil Method

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***Abstract*—This study presents a novel method to manufacture flexible electronic circuits in a continuous roll-to-roll process. Transfer foil method founds on converting processes to cut and laminate thin metal foils as designed patterns onto a target substrate. The processing technique utilizes die-cutting tools, carrier foils and adhesive films to embed functionalities with bulk metal level conductivity directly on various surfaces. Transfer foil method is a chemical-free process and operates at room temperature favoring sustainable manufacturing. Furthermore, integration of rigid electronics on transfer foil patterns is realizable by low temperature soldering as proven in the paper.**

Keywords—adhesive film, converting, die-cutting, flexible circuits, metal film, roll-to-roll

I. INTRODUCTION

Current manufacturing techniques enable fabrication of printed circuit boards (PCBs) on flexible substrates [1]. The commercially available solutions are based on etching process of copper clads with plastic base films. From these, high-priced polyimide (PI) substrate allows high performance at elevated temperatures, and polyethylene terephthalate (PET) provides an affordable alternative with limited characteristics. The industry offers manufacturing solutions for flexible PCBs also in roll-to-roll (R2R) format to produce devices with sufficient volumes and high throughput. Other alternatives for preparing flexible electronics are printing techniques, available also in R2R processes [2]. The additive manufacturing method uses inks and pastes to form functional circuits, and enables using stretchable substrates, such as thermoplastic polyurethane (TPU), to realize highly conformable structures. The known limitations of printed devices originate from the used materials with lower performance in comparison to bulk metals, for example.

This study introduces a novel method developed with VTT's research infrastructure, also known as PrintoCent Pilot Factory [3], to manufacture flexible electronic circuits. The technique called transfer foil method uses R2R converting processes and produces low-resolution circuitries at room temperature. The chemical-free manufacturing process enables using bulk metal films with a wide variety of substrate materials, such as plastics, papers and fabrics, favoring also the sustainability aspect.

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II. MATERIALS AND METHODS

A. Processing equipment

The aim of transfer foil technique is to pattern a thin metal foil with a cutting tool, to remove the excess foil, and to transfer the functional layout on a target substrate by means of an adhesive film in a continuous R2R process. A converting line from DeltaModtech [4] performs the needed operations with the six interchangeable units. The main processes with the converting line are kiss cutting and die cutting into shape, slitting a web into narrower rolls in machine direction and laminating up to four foils on the base roll. In addition, the line is integrated with a CO_2 laser unit for cutting and perforations. The DeltaModtech converting line at VTT is capable of processing rolls up to 300 mm web width at tens of meters per minute operating speed.

Figure 1. R2R converting line

B. Materials

The used materials in transfer foil process are commercially available with various metals and metal alloys at suitable roll widths. The metal layer thickness in such foils is typically ranging from micrometers to tens of micrometers and includes a thin plastic carrier film. In this study, aluminum (9 µm) and rolled annealed (RA) copper foils (18 µm) with a 23-µm PET carrier foil are in use [5].

Patterning a metal film for the designed layout is performed with a flexible die installed around a magnetic rotary cylinder. The main characteristics for a die-cutting tool are cutting angle and die height, and are adjusted separately for each material stack to be patterned. Here, SuperCut flexible dies provided by Wink [6] are used in cutting process.

From processing perspective, the method requires also adhesive films, as well as additional carrier foils and sacrificial liners to guarantee the successful R2R run. The operational principle of transfer foil method is comparable to transfer printing [7], where the adhesion between different material interfaces needs to be well-controlled. The characteristic of adhesive films in material stacks and laminates vary, but a loose adhesive is a necessity in processing steps when a carrier film and excess metal foil are detached and tacky adhesive is required when transferring and laminating functional structures on a target substrate. Pressure sensitive adhesive (PSA) films comprise the needed requirements for a tacky layer, and allow process runs at room temperature.

C. Process flow

Transfer foil method can be applied several ways depending on the targeted application. The first option is to pattern and transfer metal foil on target roll without top layer. Here, a tacky adhesive film is placed between the cut metal patterns and final substrate. The second option is to cut and laminate metal patterns directly between the two target substrates requiring more adhesive layers in the stack. Optionally, the laminate can be prepared such a way that the both sides act as carriers, and only patterned metal layer is stuck on target surface as a retrofit installation. The need or existence of top substrate has a significant effect on choosing adhesive films, positioning of adhesive layer in the stack and running order of processing steps. This affects also on number of sequential runs to prepare the final material stack.

III. Results

The capability of developed transfer foil method is demonstrated with trial runs to prepare functional electrical structures. In these runs, coil structures used in near field communication (NFC) tags are cut and transferred on a target PET film with 125-µm thickness. The inductors are prepared by using both aluminum and copper films in continuous R2R process at about 3 meters per minute speed.

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Fig. 2. Die cutting desired shape (top) and removing excess foil (bottom) in a continuous R2R process.

The achievable resolution with transfer foil method is defined by the properties of a flexible die. In particular, die height and cutting angle define the spacing between cutting edges. This distance is typically 1 mm at minimum, as with these inductor designs, and determines the realized line width and spacing after removal the excess foil. Nevertheless, decreasing the feature sizes locally is possible with laser ablation. Using a sacrificial liner over die-cut metal foil allows fine-pitch patterning with a UV laser before transferring the structure on a target substrate. Laser ablation enables forming landing patterns for surface mounted devices (SMDs), as well as local fiducials for automated assembly equipment.

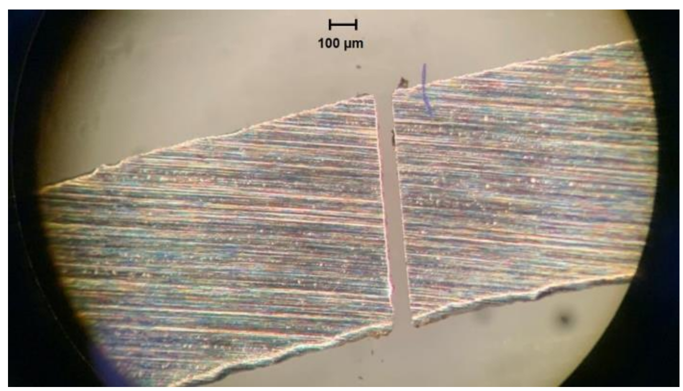

Fig. 3. Laser ablation of transfer foil.

Bulk metal layers in transfer foil method facilitates using soldering for hybrid integration of rigid electronics [8], [9]. However, the characteristics of target substrate limits solder alloy options and reflows profiles. In this study, a low temperature solder paste (SnBiAg) is used to form proper bonds between NFC chips and copper metal coils without deterioration the target PET substrate. The required peak reflow temperature with the applied alloy is 170°C-185°C opening a process window for the used PET film. Fig. 4. illustrates an outcome with manually soldered chip and tuning capacitor. The bridge connecting inductor ends and isolation layer are processed in R2R transfer foil run with manual fine-tuning.

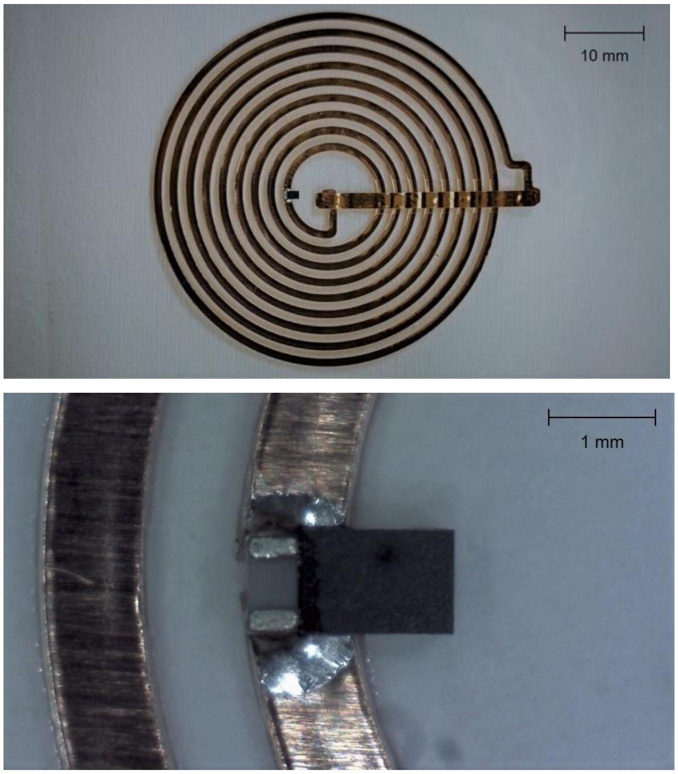

Fig. 4. NFC tag fabricated by transfer foil method.

IV. Discussion

The conducted trials proved the feasibility of transfer foil method to produce flexible electronic circuits. Integrating rigid electronics by low temperature soldering resulted in fully functional electronic systems.

In order to compare the developed processing technique to the existing ones, Table 1 lists the main characteristics of screen printing, etching and transfer foil methods in R2R processes. Transfer foil method uses mechanical die cutting tool to produce the desired patterns, whereas the other ones use masking either by a screen or photolithography methods. Due to removing of excess metal foil, transfer foil technique is considered as subtractive processing, but the waste is available in solid form and is easily collectable to further treatment. The main difference between the presented method and the existing ones is that transfer foil method uses no chemicals, nor requires elevated processing temperatures. These properties are of great importance when discussing sustainability issues with low energy consumption and minimal chemical waste.

A clear deficiency in transfer foil method is the capability to produce only low-resolution patterns. This originates from a flexible die and its profile to cut mechanically thin metal films. However, local patterning by UV-laser ablation is conceivable as an extra processing step. A major advantage in transfer foil method is the capability to laminate cut metal patterns directly also on rough substrate by means of adhesive film without a carrier foil. This widens the application area of transfer foil technology in comparison screen-printing and etching, which require smooth and low surface roughness.

TABLE I. Main Characteristics of R2R Processing Methods for Flexible Electronics

	Screen Printing	***Etching***	***Transfer foil***
Topology	Additive	Subtractive	Subtractive
Patterning method	Screen	Photolithography	Die cutting
Processing temperature	140°C	Room temperature	Room temperature
Chemical usage	Yes	Yes	No
Conductivity	<< Bulk metal	Bulk metal	Bulk metal
Resolution	200/200 µm	75/75 µm	1000/1000 µm
Substrate roughness	Low	Low	High

The next technical development steps in introduced manufacturing technique include maturing of processing multilayer structures, improving the repeatability of laser ablation and automated hybrid integration. However, The Warming Surfaces Company is commercializing the technology developed by VTT. Their main application for the technology is large area pixelated heaters integrated on the surfaces of different decoration materials. These features are enabled by the transfer foil technology capability to transfer electrical structures also on fiber based and fragile materials.

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