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Characteristics and evaluation criteria of substrate-based manufacturing. Is roll-to-roll the best solution for printed electronics?

Jürgen Willmann, Daniel Stocker, Edgar Dörsam *

Institute of Printing Science and Technology (IDD), Technische Universität Darmstadt, Magdalenenstr. 2, 64283 Darmstadt, Germany

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ABSTRACT

The vast majority of publications covering the manufacturing of printed electronics employ a web-fed roll-to-roll process. However, other principles of substrate transport are well established in printing science and industry. The focus on roll-to-roll in the scientific community therefore remains ambiguous. In an attempt to structure the discussion about upscaling organic electronics production, we extend existing classifications of substrate-based manufacturing, which is not limited to the field of printed electronics. Production processes can be classified by five key components: manufacturing technology, contact topology, substrate transport, substrate velocity, substrate feed and the degree of integration. This paper reviews four different substrate transport principles: roll-to-roll, sheet-to-sheet, sheets-on-shuttle and hybrid forms like roll-to-sheet. Besides basic working principles, both chances and limitations are discussed. Due to their individual complexity, a sound comparison ought not be reduced to a few key figures. In fact, the selection of the substrate transport requires an in-depth analysis of the individual production process. To aid decision-making, we introduce a hierarchy of 19 attributes covering aspects of production flexibility, quality, reliability, productivity and operations.

1. Introduction

Manufacturing organic electronics via printing technologies is based on the patterning of numerous specific layers onto a substrate in order to function as semiconductors, dielectrics or electroluminescent sources. Substrates itself are solid and planar materials onto which layers of other substances are applied. Depending on the application, substrates may have additional functions such as electrical insulation, conduction or physical encapsulation. Many branches of industries employ this principle in their manufacturing, e.g. graphical printing, foil coating, printed circuit boards and display manufacturing. In either case, a method for advancing the substrate through the production line is required. During display manufacturing, rigid glass-substrates are moved while functional materials are added [1]. For printing processes, flexible substrates like paper and plastic foils are transported between different printing units [2]. Printing machines utilise optimised and highly efficient principles of substrate transport. The most important substrates for printed electronics are glass and plastic foils like PET or PEN. In the future, other substrates like paper, metal or shaped substrates are conceivable.

The vast majority of publications covering manufacturing methods use a web-fed process and roll-to-roll became a slogan for high-throughput production of organic electronics [3–8]. Highly productive processes like the newspaper production are mentioned to prove the potential of printing technologies, albeit their disparate

* Corresponding author. Tel.: +49 6151162132.
E-mail address: doersam@idd.tu-darmstadt.de (E. Dörsam).

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requirements. Despite its significance, the different components of substrate-based manufacturing are currently not considered in the discussion about upscaling printed electronics production.

With device layouts and suitable materials being available, the research efforts should also be driven towards upscaling the laboratory-tested production. The design of a production system is influenced by a multitude of factors, which is why we find now to be the appropriate time to discuss their properties. Apart from the principle of transport, other components for substrate-based manufacturing can be identified to further structure the development efforts towards devices and products.

Diverse approaches are taken to transfer organic electronic production "from lab to fab" [9]. For instance, the influence of substrate materials are explored [10–12]. Several investigations address novel manufacturing technologies [13,6]. Additionally, the effect of the polymer material [9] as well as the fluid flow itself are studied [14].

The purpose of the present investigation in this context is to provide a holistic manufacturing classification for organic electronics. Classification facilitates the grouping of experiments and their comparability by a clarified communication [15]. Additionally, new fields of research can be identified to design efficient production processes [16]. Currently, several classification attempts for printed electronic production can be identified in the literature.

Søndergaard et al. focus on substrate transport principles and group published experiments into "true" roll-to-roll (R2R), R2R-"compatible" and non-R2R-processing [3]. Chang et al. mainly regard the manufacturing technologies and differentiate between subtractive and additive processes [17]. In order to compare manufacturing processes for printed electronics our classification incorporates the existing approaches and extends them by several other components.

The remainder of this paper is organised as follows. In Section 2 we introduce a classification of substrate-based manufacturing containing several key components. Section 3 outlines technical aspects, chances and limitations of four established substrate transport principles. Section 4 presents a hierarchy of criteria for the evaluation and selection of substrate transport principles based on requirements specific to the product. Section 5 summarises our findings and provides some concluding comments.

2. Classification of substrate-based manufacturing

Substrate-based manufacturing processes consist of six key components: manufacturing technology, contact topology, substrate transport, substrate velocity, substrate feed and the degree of integration. These components are mostly independent of each other and characterise any substrate-based manufacturing-process. Combining the components allows for several dozen possible manufacturing process designs. Hence, the current discussion about upscaling the production of printed electronics covers only a fraction of this solution space. Fig. 1 depicts the components and their corresponding characteristics. In the following sections, we describe the classification before we provide a more detailed overview of substrate transport principles.

The *manufacturing technology* describes the principle, by which a defined and distinct pattern is applied onto the substrate. Numerous manufacturing technologies can be used for printed electronics and many new technologies are feasible. We distinguish three main groups: additive, subtractive and structuring manufacturing technologies. Additive manufacturing technologies are for

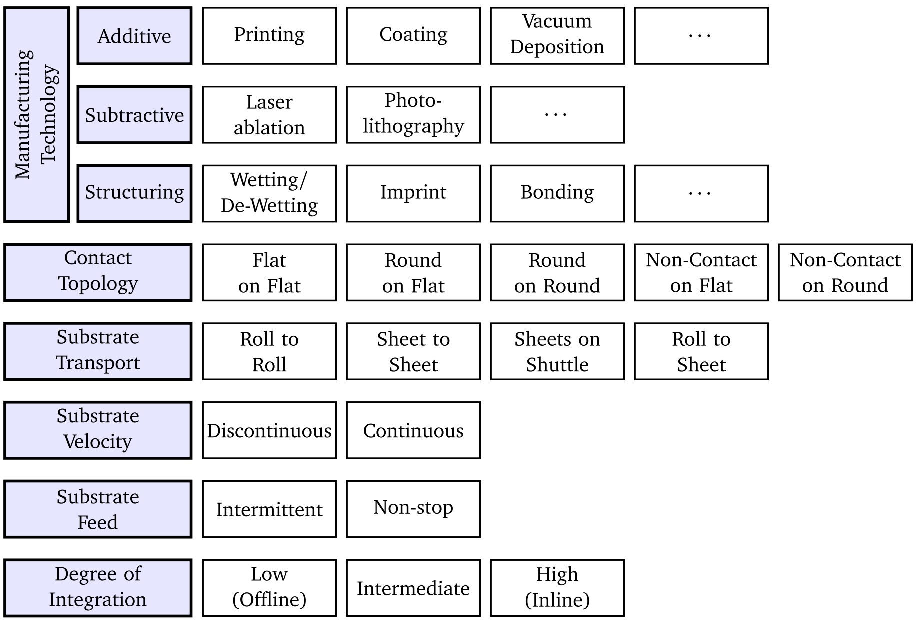

Fig. 1. Classification of substrate-based manufacturing processes.