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Research Paper

Three dimensional printed electronic devices realised by selective laser melting of copper/high-density-polyethylene powder mixtures

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ABSTRACT

A manufacturing process with the capability to integrate electronics into 3D structures is of great importance to the development of next-generation miniaturised devices. In this study, Selective Laser Melting (SLM) was used to process copper/high-density-polyethylene (HDPE) powder mixtures to build conductive tracks in a 3D circuit system. The effects of copper/HDPE volume ratio, laser input power and scanning speed on the resistivity of CO_2 laser processed tracks were investigated. The resistivity of the tracks decreased from $26.6 \pm 0.6 \times 10^{-4}$ Ωcm to $1.9 \pm 0.1 \times 10^{-4}$ Ωcm as the copper volume ratio increased from 30% to 60%. However, further increasing the copper ratio to 100% resulted in poor conductivity. The lowest resistivity was achieved with an input power of 20 W and scanning speed of 80 mm/s. Additionally, processing using single-track-scanning and raster-scanning programs was compared; the overall energy distribution on the surface was more uniform using a raster-scanning program, which further reduced the resistivity to $0.35 \pm 0.04 \times 10^{-4}$ Ωcm. Based on the results, a 3D multi-layered circuit system was manufactured with the HDPE as the substrate/matrix material and copper/HDPE mixture as the conductive-track material. This circuit system was successfully manufactured, demonstrating the possibility of using SLM technology to manufacture dissimilar materials towards 3D electronic applications.

1. Introduction

A printed circuit board (PCB) is typically a two-dimensional (2D) system that interconnects electronic components using conductive tracks laminated onto a dielectric substrate. However, the increasing demands of small-scale electronic devices, such as mobile communications, smart home appliances and military equipment, require miniaturization that can be further achieved by moving towards three-dimensional circuit configurations with simultaneously improved performances. Double-sided and multi-layered PCBs are widely used to reduce the circuit volume and components have also been embedded within the layers to save space on the surface, but these still retain a largely 2D (2.5D) format (Etienne and Sandborn, 2007). To move towards 3D devices, flexible substrates have been used that enable circuits to fold around/inside other parts of an assembly (Siegel et al., 2010). In addition, moulded interconnect devices (MIDs) have been created that involve the deposition of circuit patterns on the surface of injection moulded parts with non-planar shapes that, for example, form the structure of the product casing (Chen and Young, 2013). However, many of the currently available manufacturing processes for PCBs have long production cycles due to the requirement for tooling and involve subtractive processes with associated waste, for example, from photolithography and metal etching steps, or may use solvents that are incompatible with some polymer substrates (Ko et al., 2007).

With the growing demand to integrate electronics within the fabric of products, that may themselves have novel form factors, there is an ever increasing need to develop technologies able to embed electronic circuitry directly into a wide range of materials and structures. Additive Manufacturing (AM) allows the creation of 3D objects by forming successive layers from pre-designed digital models. This technology has already transformed the concept of conventional manufacturing production and made significant impacts on various industries including aerospace, medical implants, automotive, construction and art design (D'aveni, 2013). Due to its ability to manufacture complex geometries, AM has the potential to produce 3D electronic devices by depositing conductive tracks within a 3D dielectric matrix. This process is also environmentally friendly with minimum manufacturing loss produced. Previous studies used stereolithography (SLA) to build substrates with slots designed for the integration of electrical components that were subsequently connected using a conductive paste deposited by micro

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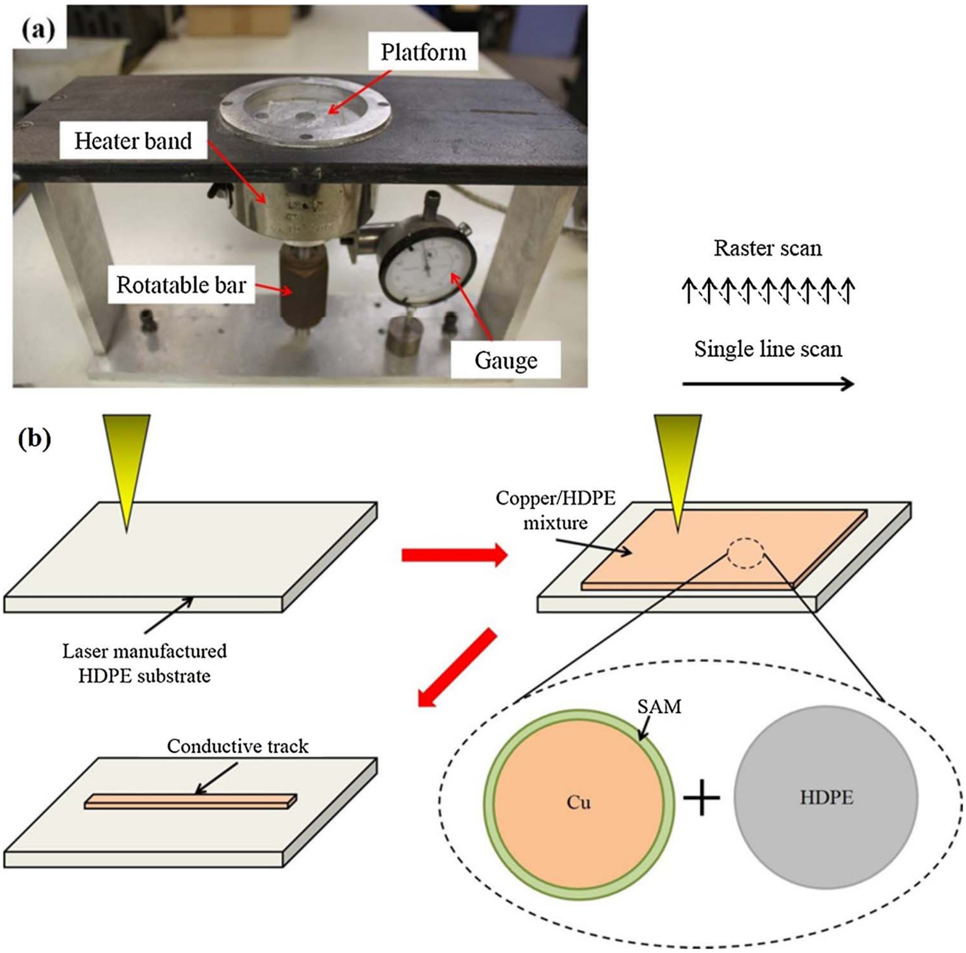

Fig. 1. (**a**) The build platform for the SLM process and (**b**) schematic diagrams of the SLM of copper/HDPE powder to form a conductive track on an HDPE substrate. The mixture of HDPE and SAM coated copper particles in the powder bed is highlighted. A diagram of the laser path for the single line and raster scan patterns is also included.

dispensing (Lopes et al., 2012). By repeating the cycle of these two processes it was possible to manufacture a complete 3D embedded circuit. As an alternative to conductive paste deposition, a more flexible AM technology is drop-on-demand (DOD) inkjet printing, which deposits droplets of polymer solution (Ko et al., 2008) or nano-metal suspension (Cui et al., 2010) onto a substrate. This technique is only suitable for 2D or micro-3D circuit printing due to the small droplet size and the restriction of ink viscosity (Park et al., 2007). However, with both pastes and inks, an additional thermal curing step using, for example, an oven, hotplate or laser, is usually required to sinter the nano-metal deposits (Mun et al., 2012) or cure the adhesive pastes (Sanchez-Romaguera et al., 2008) and this can limit the range of suitable substrate materials.

A key challenge in 3D printing of embedded electronic devices is to develop a process that is capable of manufacturing cost effective metallic conductors, can be integrated with the build-up of 3D dielectric material and be compatible with the wide range of potential substrate materials and form factors demanded by the end applications. Selective Laser Melting (SLM) is a laser-based computer controlled additive manufacturing technology used to build 3D objects with complex geometries from powders. SLM has the potential to manufacture dissimilar materials by spreading powder layers with different materials during different stages of the process (Liu et al., 2014). In the study reported here, SLM was used to create conductive tracks from a copper and high-density-polyethylene (HDPE) powder mixture, which was simultaneously incorporated within a HDPE dielectric matrix to form an overall 3D embedded circuit architecture. Due to its monochromatic and coherent properties, the laser can be used to generate highly localised heat to create desirable patterns during manufacturing and in this study, a low cost CO_2 laser was utilized as it was found to be capable of processing both the copper and HDPE powder materials. To avoid the use of high cost nanoscale metals, such as gold and silver, micron scale copper powder was selected in this study to create the conductive tracks. A continuous pathway of particles is required so that the electrons can move freely between them to offer high conductivity. However, the oxide formed on the copper surface can create a highly resistive barrier between particles and therefore a pre-treatment of the powder surface was carried out to remove the oxide layer and restrict re-oxidation by the application of a self-assembled monolayer (SAM) organic coating (Hutt and Liu, 2005). This facilitates the use of the copper particles in air and, during exposure to the laser beam, the coating is believed to be displaced enabling clean copper surfaces to come in to contact. Good adhesion between the conductive pattern material and the dielectric matrix is important to support the structures and it was proposed that this can be achieved using the same polymer binder to establish the matrix and the supporting structure for the conductive particles. Nylon-12 (or polyamide-12) is the most commonly used polymer material in SLM processing due to its broad 'superheating region' (Caulfield et al., 2007). However, nylon products manufactured using SLM usually have a relatively high porosity of between 5 and 10% due to high water content (Goodridge et al., 2012), which could present long term reliability issues. Therefore, an HDPE powder was used in this study as the substrate material as well as the binding material within the conductive track (Bai et al., 2016). A systematic analysis of the effects of copper/HDPE ratio, laser input power, scanning speed, and scanning program on the electrical conductivity and microstructure of the resulting conductive tracks was carried out in order to understand the mechanism of powder melting and consolidation during the laser process. The outcome of this study will contribute to the manufacturing of functional 3D electronics from dissimilar