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Ultraprecision machining of gravure roller mould for roll-to-roll printing of high-resolution electronics

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Abstract
Printing electronics has attracted great attention in recent years. Roll-to-Roll gravure printing is able to transfer conductive nanoparticle ink onto the flexible film substrate to form continuous fine metal lines using a gravure roller mould. However, it is difficult to scale down the printed line width, which is crucial for the film's various performances, because of the large size of gravure cells on the roller. In this study, a novel method based on ultraprecision machining technology, Diamond Micro Engraving (DME), is introduced to miniaturize the gravure cells. Through applying the DME process, generation of consistent cell structure is achieved, and the width of engraved gravure cell is successfully miniaturized to 7µm. With the optimized cell spacing, the DME-machined roller moulds are used in gravure printing of metal mesh film. The printed line width is reduced from 47µm to 19µm, and the transmittance of the printed metal mesh film for visible light is increased from 65.2% to 80.4% accordingly.

Keywords: Ultraprecision diamond machining; Slow Slide Servo; Roll-to-Roll gravure printing; Metal mesh film

1. Introduction

Printing electronics provides a better alternative to realize low-cost and high-volume manufacturing of a wide range of flexible and costless electronic systems. For printing of high-performance electronics, it has been found that scaling down of the printed features is essential because smaller printed features will provide higher circuit density, higher transition frequency of transistors and lower operating voltages [1-2]. Gravure printing of electronics employs a high-precision gravure roller mould to transfer conductive nanoparticle ink onto flexible substrates using engraved gravure cells on the roller, and the printed feature size is directly determined by the ink volume transferred, which is accordingly determined by the gravure cell size [3]. However, a common limitation of the three conventional engraving techniques (laser engraving, chemical etching and electro-mechanical engraving) is that the engraved cell size is usually larger than 25µm, and this is resulted from the large spot size of laser beam, the inaccurate engraving machine system, the material removing mechanism, and so on.

Ultraprecision diamond machining has been widely used in generation of mirror quality surface and sub-micron profile on workpieces made of many engineering materials through various machining processes such as turning, milling, fly cutting and diamond micro chiselling [4]. In this study, a novel method based on ultraprecision machining, Diamond Micro Engraving (DME), is developed to realize miniaturization of gravure cells on high-precision gravure roller moulds for R2R printing of fine line electronics. Micro engraving is realized using a V-shape sharp diamond tool with customized geometrical shape to continuously generate concave inverted pyramid structures on the roller surface using an ultra-precision machining system. Based on geometrical modelling of the DME process, CNC tool path program is generated taking into account all the relevant parameters regarding the gravure pattern, cell, tool, and roller. By employing DME, gravure rollers with consistent sub-10µm cells are successfully fabricated and are also applied in R2R gravure printing of metal mesh as a kind of transparent conductive film. Sub-20µm printed line width is achieved, and transmittance of the printed metal mesh film has been increased to 80% accordingly.

2. Diamond Micro Engraving (DME)

2.1. DME process

The general idea of DME is to use a V-shape sharp diamond tool to remove material from the roller surface with a single step of cutting motion, and to produce a gravure cell with a concave inverted pyramid microstructure. Continuous engraving of cell pattern is realized by rotating the roller to the required angular position with C-axis and positioning the tool with the linear axes of X- and Z- (see Figure 1). The concave cell structure is designed to have a square-shape top surface with an equal cell width of and a structure height of *h*. For obtaining such a structure, the bisecting line of the V-shape diamond tool should be set to be perpendicular to Z-axis, which is achieved by adjusting the B-axis assisted with an optical inspection system. Precise control of interactive movement of the tool and the roller using the Slow Slide Servo technique enables micro engraving of consecutive gravure cells with consistent structure and accurate dimensions possible.

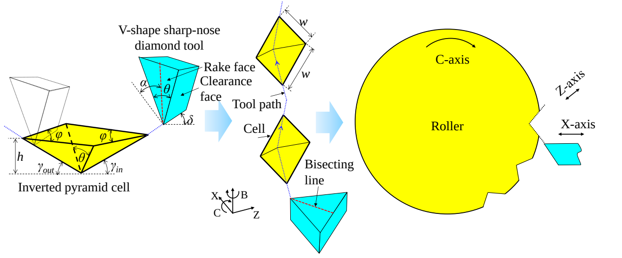

Figure 1. DME process kinematics and relevant parameters for cutting concave inverted pyramid cells on a gravure roller mould.

2.2. DME using ultraprecision machining system

In this study, a 5-axis ultraprecision machine system (*Moore Nanotech 350FG*) is utilized to realize DME of the above gravure pattern which is composed of tens of thousands of cells on a metal roller mould. The CNC tool path for the DME process is generated considering the specified gravure pattern, cell structure and dimensions (width, height and spacing), tool dimensions and location, and roller dimensions (diameter and length). Then, according to the generated CNC tool path program, DME is conducted to engrave the designed gravure pattern at specified positions on the roller surface. Finally, the machined gravure cylinder is measured to evaluate quality of the engraved pattern and consistency of the cell size and structure.

3. Ultraprecision machining of gravure pattern by DME

The mesh pattern and engraved cells on the machined roller are inspected using an optical microscope as well as a scanning electron microscope (SEM). As an example, Figure 2 shows images of the gravure roller, the captured mesh pattern, and the engraved cells, which are taken by camera, microscope and SEM, respectively. By employing the proposed DME process, it is easier to realize cell size miniaturization than the other conventional engraving techniques. In this study, efforts are spent in miniaturizing the engraved gravure cells by reducing the engraving depth and meanwhile maintaining the consistence of cell structure and avoid the burr formation. The yet smallest cell width with consistent cell structure and burr-free profile achieved by DME using the 120^{o} diamond tool on this brass roller is 7µm, as shown in Figure 3.

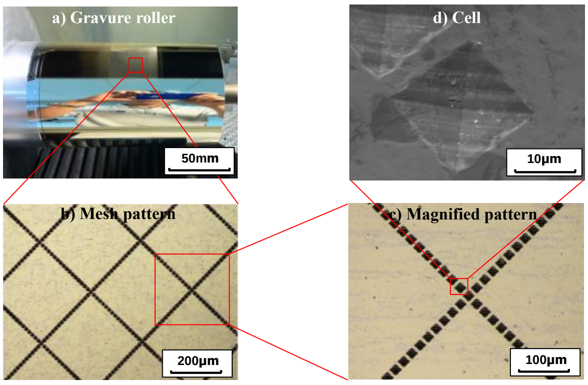

Figure 2. Camera, microscope and SEM images of roller, mesh pattern (50×50mm2) and cells (18µm width) machined by DME.

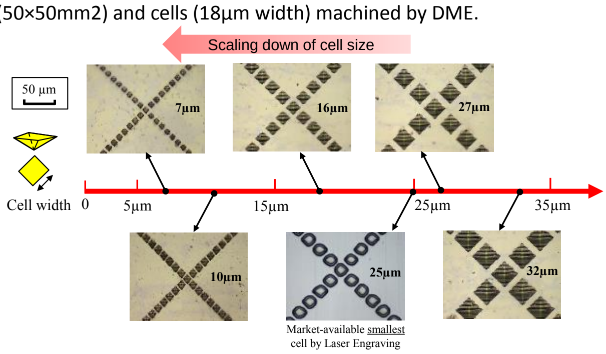

Figure 3. Miniaturization of gravure cell size by DME.

4. Gravure printing of metal mesh using fabricated rollers

After demonstrating the capability of scaling down the gravure cell size using DME, several printing tests were conducted to evaluate the performance of engraved gravure rollers in printing the metal mesh film. Figure 4 shows three microscope images of printed metal mesh using a market-available gravure roller machined by laser engraving (25µm cell width) and two rollers machined by DME (16µm and 10µm cell width). It can be observed that the laser-engraved roller (25µm cell width) provides the widest printed metal lines. Using the rollers engraved by DME with smaller cell width, the printed line width can be continuously reduced. Finally, metal mesh with consistent 19µm line width is achieved with no ink overflow or broken lines.

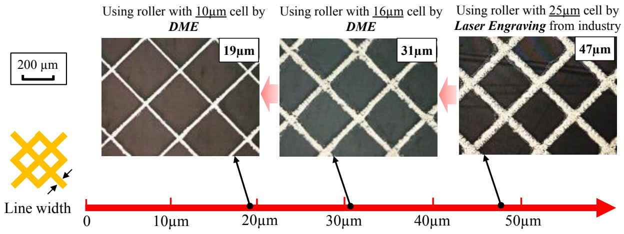

Figure 4. Scaling down of printed line width using gravure rollers machined by DME.

Transmittance with respect to visible light is an important feature of transparent conductive film used in touch screen modules. Its value should be at least greater than 80% to allow enough light passing through the film. Transmittance of the metal mesh is mainly determined by the covering percentage of non-patterned area which allows the penetration of light. In this study, the transmittance of the printed films is measured using a UV-VIS Spectrophotometer, and the results are shown in Figure 5. The average transmittance of printed metal mesh film in the visible light region is increased from 65.2% to 80.4%, which is comparable to the transmittance of ITO transparent conductive film (typically ≥80%).

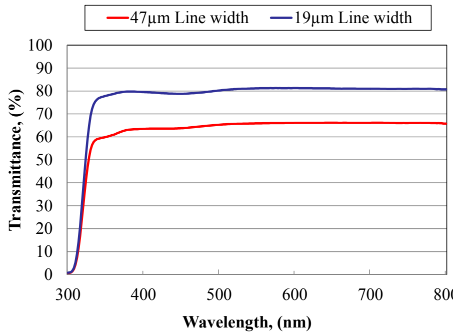

Figure 5. Transmittance of metal mesh films printed using rollers engraved by DME (19µm line) and laser engraving (47µm line).

5. Summary and outlook

In this paper, Diamond Micro Engraving, a novel method to realize engraving of high-precision gravure roller based on ultraprecision machining technology, has been introduced. By employing DME, cell size miniaturization on gravure roller moulds is achieved, which accordingly scales down the feature width of printed metal lines in roll-to-roll gravure printing of electronics (e.g. metal mesh).

The potential of the DME process was demonstrated in this study. However, additional research should be conducted in order to further reduce the cell size, and to increase the machining speed by applying Fast Tool Servo technology.

References

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