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Hot embossing of micrographic elements in polypropylene

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Abstract

Micrographic features generated by electron beam lithography have been hot embossed in biaxially-oriented polypropylene (BOPP). Each micrographic element consisted of a sub-field of 30×30 μm with a specific configuration of symbols, lettering and graphics. The micrographic elements were integrated with arrays of diffractive gratings in the form of an optically variable device. A high quality embossing of various micrographic elements has been demonstrated in features with a linewidth dimension $\geqslant 365$ nm and depth $\geqslant 255$ nm. The replication of arrays of micrographic elements was achieved uniformly over an area of 20×20 mm in the BOPP film by embossing at a temperature of 130 °C.
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Keywords: Hot embossing; Micrographic; BOPP

1. Introduction

Hologram images based on diffraction gratings have become widely used as security devices [1]. The grating structures have typically been embossed into metallised foil as the carrier for the iridescent image. In these foil-based holograms, the grating pattern has predominantly comprised a dot-matrix diffractive array generated by laser interference lithography [1]. In recent years, the use of electron beam lithography (EBL) in the fabrication of diffractive security images has enabled the introduction of a range of kinematic and optically variable effects not able to be produced by traditional holographic techniques [2,3]. These optically variable devices (OVDs) have comprised pixellated grating structures which give a variation in diffractive image with change in viewing angle. Another unique feature of the optically variable images produced by EBL has been the inclusion of micrographic elements as a part of the structure [2,3]. The pixel-sized micrographic elements have contained a combination of micron-scale graphic shapes and symbols ranging in size from 1 to 30 μm [2]. The function of the micrographic elements has been to produce a diffuse scattering effect in the regions surrounding the grating-based diffractive image. Recently, Leech has reported the embossing of grating-based optically variable devices (OVDs) in transparent biaxially-oriented polypropylene (BOPP) film [4]. The embossed structures have produced a switch in diffractive image when viewed in transmitted light [4]. We report here on the novel hot embossing of micrographic elements with various features in BOPP film. The ability to emboss micrographic elements in BOPP represents a key component in the fabrication of transparent OVDs for applications in polymer banknotes and cards.

2. Experimental details

The micrographic elements used in these experiments were introduced at the stage of the initial artwork within the format of an Adobe Photoshop file. Each sub-field of 30×30 μm within an optically variable device was assigned a microstructure element which contained either a grating array with specific groove width/curvature or a micrographic element. The features within an individual micrographic element consisted of a combination of graphic images, alpha-numeric characters and line drawings [2]. An OVD with typical dimensions of 20×20 mm contained

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up to 100,000 individual micrographic elements. The exposure of the OVDs was performed using a Leica EBMF10.5 system in a 500 nm layer of EBR-9 resist (Toray, Japan) at a dose of 24 μC/cm^2 and 30 keV. After electron beam exposure, the plate was developed in 1:1 MIBK:IPA solution for ~150 s. The resulting relief structure defined in resist was then replicated as a nickel shim. Initially, a thin film (~100 nm) of Ni was dc sputtered onto the surface of the resist followed by electrodeposition of a thicker layer (~150 μm, hardness ~265 HV) [5]. Subsequent dissolution of the resist layer in acetone allowed the release of the shim as a reverse profile. A further copy of the shim then provided the same relief pattern as the original plate. The nickel shims were used as embossing plates between two heated platens (100 mm × 100 mm) at 120 kN force and 130 °C. The workpiece in these experiments comprised a film of biaxially-oriented polypropylene (BOPP) of ~60 μm thickness. These conditions of embossing were previously shown to produce high quality gratings in BOPP [4]. In each embossing experiment, the pressure and temperature were held constant for 60 s with subsequent cooling of the platens to 50 °C and de-embossing of the replica. Scanning probe microscopy (Digital Instruments D3100) and scanning electron microscopy were used in examination of the structures.

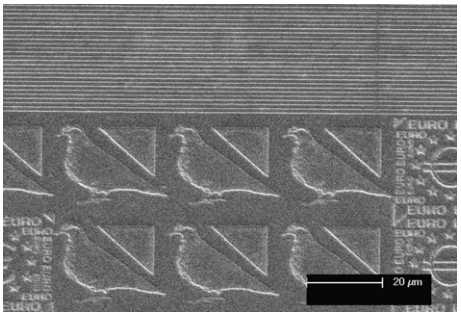

Fig. 1. Array of micrographic elements and gratings embossed in BOPP.

3. Results and discussion

Fig. 1 shows an array of embossed micrographic elements which were comprised of either a dove image or a Euro Test image. The 30 μm pixels were arranged in a configuration which combined both of these types of graphic element together with pixels of gratings as shown in the upper part of Fig. 1. As evident in Fig. 1, both types of micrographic element were uniformly embossed across the image. A similar level of uniformity in the embossed elements was produced across the entire 20 × 20 mm area of OVD images. Fig. 2 shows an example of a single micrographic element comprising a dove image as (a) an exposure in EBR-9 resist by electron beam and (b) an embossed replica. Although the lateral dimensions of the dove were ~25 μm, the design has also included finer features such as the detail of the eye with a diameter of ~1 μm. The exposed outline of the body of the dove shown in Fig. 2a was developed to a depth of 500 nm in the resist. The corresponding embossed pattern was obtained using a reverse copy of the shim, which produced a protruding relief in the replica. Finer features such as the eye and the feet of the bird were clearly visible in the embossed image. The height of the embossed replica in BOPP was measured by a Veeco Dektak6M profilometer as 395 ± 40 nm. The reduced height of the embossed regions compared with the depth of the image in the original plate has been attributed to a relaxation of the BOPP film following release of the embossing force.

Fig. 3 shows a micrographic element based on a Euro test theme. In Fig. 3, a comparison has been made between (a) an exposed image in e-beam resist and (b) a corresponding embossed region. Among the features in the design of this element were the large Euro symbol (12.5 μm length), the fine vertically aligned lettering (1.5 μm length, 0.5 μm

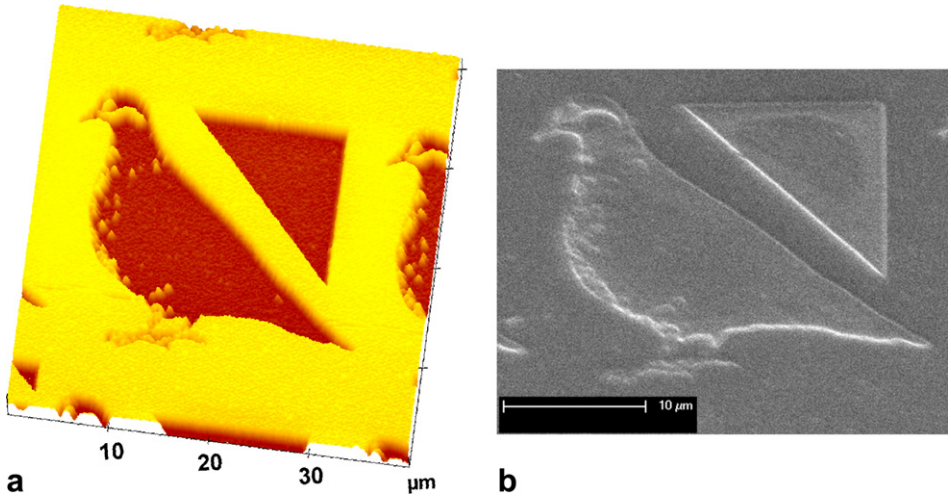

Fig. 2. A single micrographic element featuring a bird image (a) as an e-beam exposure and (b) embossed in BOPP film.

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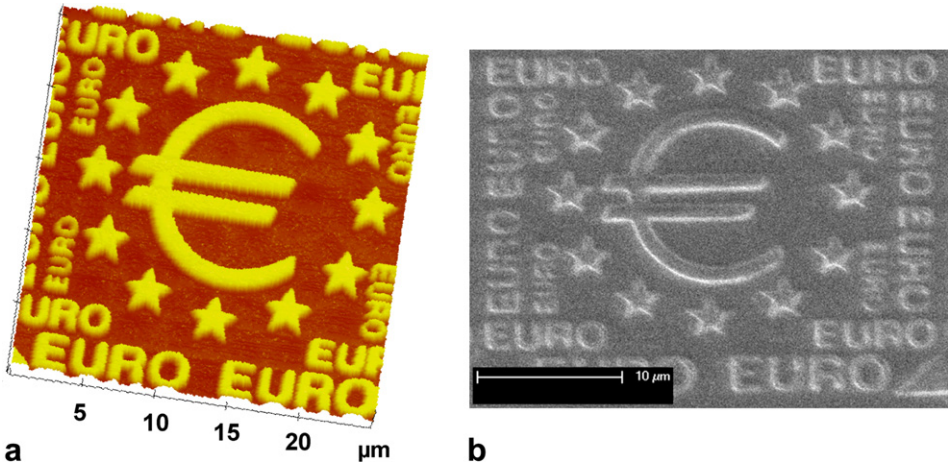

Fig. 3. Micrographic element featuring a Euro image (a) as the initial Ni shim of the e-beam exposure and (b) embossed in BOPP film.

line-width) and star symbols (3 μm width), all of which have been replicated in detail in BOPP. In both the initial Ni shim and the embossed replica, the relief features were protruding from the surface. In this micrographic element, the depth of the features in the e-beam plate was ~500 nm as shown in the SPM trace in Fig. 4. The sidewalls of the relief were essentially vertical with a plateau shape at the top of the peaks. In comparison, a series of profilometer scans on the embossed image in BOPP have measured an average depth of structure of 405 ± 40 nm. This difference in height between original plate and embossed structure again has been attributed to an effect of relaxation during de-embossing rather than other explanations such as incomplete filling of the mold. The images of the embossed structures have shown no sign of ridges or shunts which may indicate an incomplete filling.

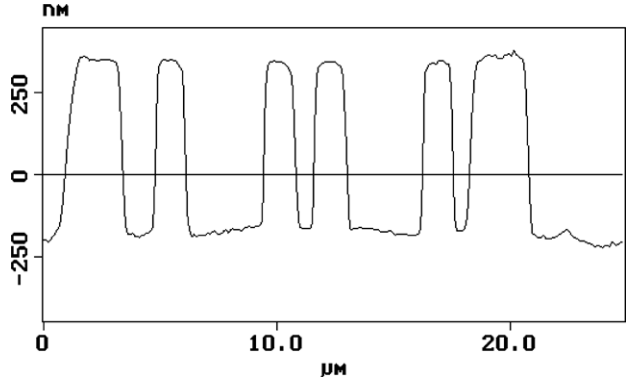

Fig. 4. SPM profile of the Euro micrographic element as shown in Fig. 3a.

Fig. 5a shows a single micrographic element which comprised an array of numbers, each with a length dimension of 4 μm and line-width of ~0.75 μm. The average depth of the numerals in the original plate was ~380 nm. Fig. 5b shows that the features in each of the numbers were accurately replicated in the BOPP film. The relatively smooth surface of the embossed image has indicated a clean separation from the shim during de-embossing without tearing or adhesion at the interface. The embossed combinations of numbers have added a further inherent security feature in addition to the role of providing an

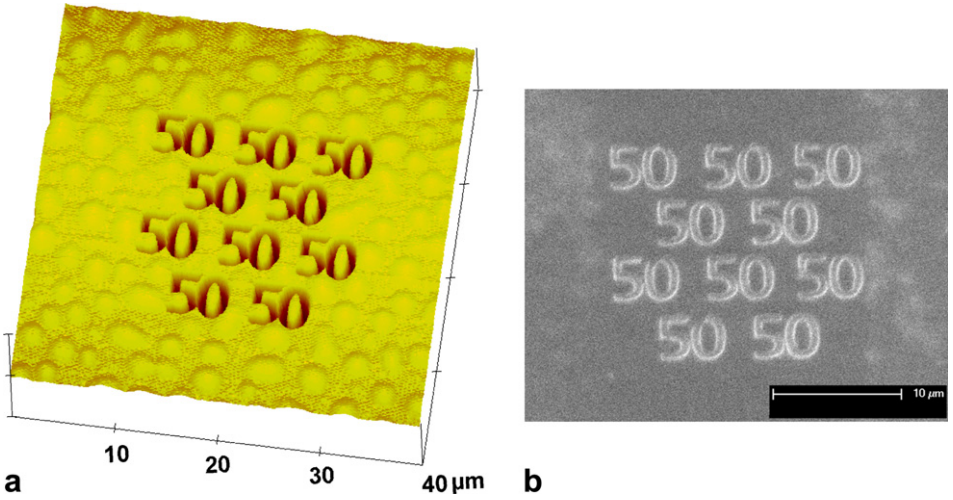

Fig. 5. Micrographic element comprised of numeric array (a) exposed by e-beam and (b) hot embossed in BOPP film.

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optical effect in the film. The repetition of the numbers throughout the film enables authentication even of small areas by microscopic examination. Fig. 6a shows another micrographic element containing the Euro symbol which incorporated a finer pattern than included in the design in Fig. 3. The Euro symbol in Fig. 6 was measured as 6 μm in length with a 2 μm line-width while the surrounding stars were 1.5 μm in width. Fig. 6b shows that the embossed structures have produced an accurate replication of the pattern although with some loss of fine detail in the vertices of the stars. In the vertices, the features reduced to a point with widths $\leqslant$250 nm. Fig. 7a shows another type of micrographic element which comprised an array of fine lettering (365 nm average linewidth, 120 nm depth). The individual text features shown in Fig. 7a were contained within a single pixel of 30×30 μm. However, the embossing of these text characters has resulted in a raised ridge with only indistinct detail within the groups of letters (Fig. 7b). The inability to emboss these very fine letters has also been attributed to a thermal relaxation of the BOPP film after release from the shim. In previous studies, there have been several reports of structures with dimensions of $\leqslant$100 nm formed by hot embossing in PMMA (for example, Ref. [6]). But a property of polypropylene is the significantly higher coefficient of thermal expansion (12.4×10^{-5} mm/mm/°C) than other thermoplastics such as PMMA (8×10^{-5} mm/mm/°C) and polycarbonate (6.8×10^{-5} mm/mm/°C). The results therefore indicate a larger minimum feature size was required for hot embossing in polypropylene than in PMMA.

In Table 1, the dimensional features of each of the micrographic elements have been summarised together with an assessment of the ability to emboss in BOPP. Included in Table 1 was an additional micrographic element (element 6) which comprised a patterned array of fine lines. This element has been included as an example of a feature with a depth <100 nm. The fine lines failed to emboss as consistent with the results for the very fine lettering (element 5 in Table 1). The results have indicated that micrographic features with linewidths of $\geqslant$350 nm and

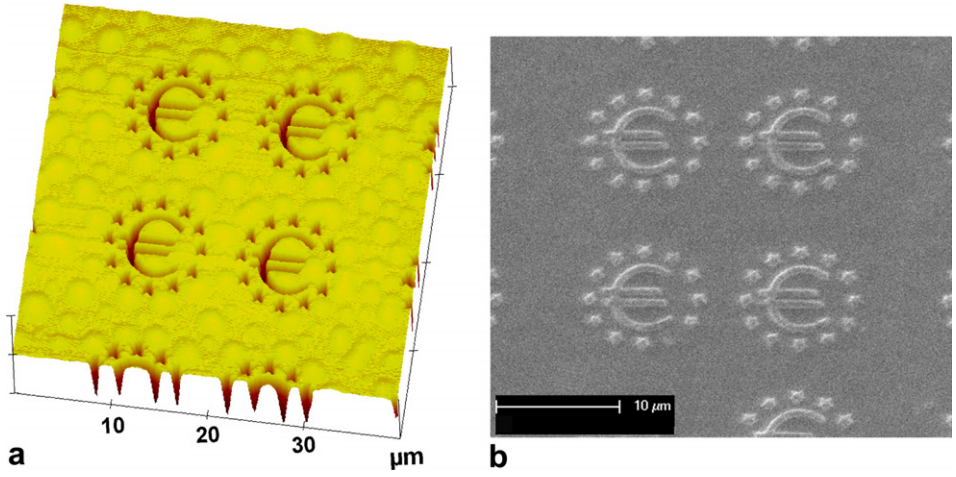

Fig. 6. (a) E-beam exposed array of small Euro symbols and (b) embossed replica.

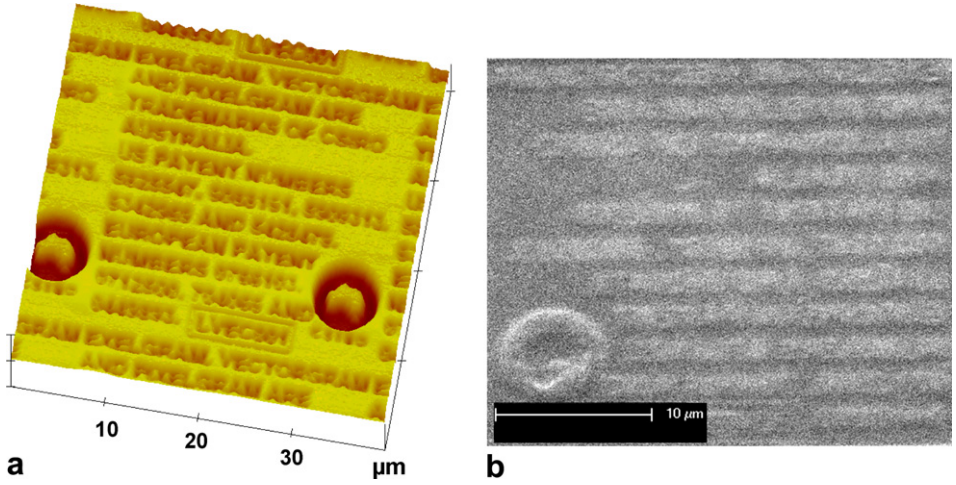

Fig. 7. Micrographic element comprised of lettering (a) as exposed by electron beam and (b) after embossing in BOPP.

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Table 1
Summary of micrographic elements and ability to hot emboss in BOPP

Micrographic element	Dimensional features	Depth (nm)	Emboss in BOPP
1. Bird image	Fine (eye) – 1 μm length Coarse (body) – 25 μm	255 500	Yes
2. Euro (large)	Fine letters – 1.5 μm length, 350 nm linewidth Euro symbol – 12.5 μm length, 1.25 μm linewidth	435 500	Yes
3. Array of numbers	4 μm length, 625 nm linewidth	380	Yes
4. Euro (small)	Symbol – 6 μm length, 2 μm linewidth Stars – 1.5 μm width	470 411	Yes
5. Array of letters	1 μm length, 350 nm linewidth	120	No
6. Graphic line image	350 nm linewidth	85	No

depth of $\geqslant 255$ nm were necessary in order to retain a definition of structures during embossing in BOPP.

The results have given no indication of an orientation effect of the film on embossing characteristics of the elements. The morphology of BOPP film after stretching comprises a fibre-like network oriented in the transverse-draw and machine-draw directions [7]. A localised deformation of BOPP film at room temperature using an indenter has resulted in a re-orientation and a compaction of the polymer strands in direction of the shear force [8]. The molded surfaces presented in Figs. 1–7 have shown a smooth embossed surface without evidence of a fibrous structure. The large compressive force associated with embossing of the BOPP film has evidently resulted in a compaction and re-orientation of any fibrous structure in a direction parallel to the Ni shim. The extent of this compaction was evidently the dominant factor in determining surface relief rather than any effects of prior orientation of structure in the film.

4. Conclusions

The hot embossing of micrographic elements comprising graphic shapes, numbering and lettering has been demonstrated in biaxially-oriented polypropylene film. The individual micrographic elements consisted of arrays of 30×30 μm pixels in which features were defined by electron beam lithography. High quality embossing was obtained with feature linewidths of $\geqslant 350$ nm and depth $\geqslant 250$ nm at 130 °C. The inability to emboss structures with a depth <120 nm has been attributed to relaxation of the BOPP during de-embossing. The embossing of micrographic elements in BOPP represents a key component in the fabrication of transparent OVDs for applications in polymer banknotes and cards.

Acknowledgements

SEM images were obtained by M. Greaves.

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