

IMPRINTING APPARATUS AND METHOD

FIELD OF INVENTION

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The present invention relates broadly to an imprinting apparatus and method, and to a method for fabricating an imprint drum for an imprinting apparatus.

10 BACKGROUND

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Roll-to-roll nanoimprinting is a very promising platform technology for high throughput micro- and nano-fabrication. It is typically used to pattern a continuous substrate, generally a thin and flexible plastic web, with micro- to nano-scale structures.

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Figure 1a shows a schematic diagram illustrating a conventional roll-to-roll nanoimprinting system 100. In the system 100, structures 110 are produced by depositing a UV curable resin coating 102, using a dispensing unit 101, on a plastic web or substrate 104 and then pressing a mold 106 with the desired patterns into the resin coating 102, forcing the resin to fill and conform to the contour of the mold cavities. The resin is then exposed to UV radiation provided by a UV lamp 108, causing it to cure and form a solid, textured coating on the plastic web 104 upon removal of the mold 106. The system 100 may also include pressure rollers 112a, 112b and a demolding roller 114 to assist the imprinting process, as shown in Figure 1a.

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The conventional system shown in Figure 1a may suffer from several drawbacks. For example, a significant amount of resin may be wasted because the resin is dispensed over most or the entire web 104, but often smaller areas are imprinted. Resin consumption is the most expensive consumable in absolute terms in the production process because the chemicals are expensive to manufacture and are not re-used, particularly after being subjected to UV curing. Also, it is very

difficult to dispense the resin only on selected spots on the web or substrate 104 because the dispensed droplets on the web 104 need to be precisely aligned and timed to join with the mold 106 at exactly the right moment when the web 104 and mold 106 are pressed together by the pressure rollers 112a, 112b.

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Furthermore, because the roll-to-roll process involves the joining of surfaces in motion (e.g. the mold 106, the resin coating 102, and the substrate web 104), defects due to trapped air can take place, especially when this joining process is carried out in normal atmosphere (no vacuum, no low atomic weight, inert gases).

10 This may increase the reject rate, and therefore the cost of production. There may be a variety of attempts to mitigate or eliminate this problem, including the use of vacuum and low atomic weight, inert gases at the point of joining. However, such techniques may require additional components and/or controlled environment, which may increase the complexity and cost of the system.

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Another conventional method that may not require the use of UV curable resin involves thermal roll-to-roll nanoimprinting, in which patterns are typically replicated by heating a roller mold with surface features and pressing it against a continuous thermoplastic polymer web (or more rarely, a thermoplastic polymer
20 coating). Commonly used thermoplastic materials include polyethylene terephthalate (PET), polypropylene, polystyrene, polycarbonate, polymethyl methacrylate (PMMA), cyclo olefin polymers and copolymers. Because the materials used in this approach tend to have high viscosity at room temperature, heat is generally applied to raise the temperature of the molded material above its glass transition
25 temperature in order to cause the material to flow under the pressure of the applied mold to form a replicated pattern. In thermal roll-to-roll nanoimprinting, the web is often pre-heated prior to reaching the mold, where the web is embossed at its process temperature. Because the applied pressure is generally large (at least 5 MPa), metallic molds such as nickel are typically used because of their relatively
30 high elastic modulus.

Figure 1b shows a schematic diagram illustrating a conventional thermal roll-to-roll imprinting system 150, suitable for use with thermoplastic polymer webs. In this system, a roller mold 152 can be obtained by wrapping a sheet mold around the

roller 154 or by directly writing features onto the roller surface (for obtaining a seamless roller). Typically, the thermoplastic web 156 is pre-heated to just below the glass transition temperature (T_g) of the web 156, while the roller mold 152 is heated well above T_g to enable the polymer to flow into the mold cavities. Pressure is applied to the web 156 either by pressing the roller mold 152 against a conformal backing roller 158 (as shown in Figure 1b), or by rigidly fixing the two rollers 154, 158 to control the gap width between them to be slightly narrower than the thickness of the web feed 156. In the 2-roller setup shown in Figure 1b, heating, imprinting and demolding processes usually are all integrated into the scanning action of the roller 154.

One of the difficulties encountered with conventional roll-to-roll nanoimprinting systems, such as those shown in Figures 1a and 1b, is in obtaining a large sheet mold in order to wrap the mold completely around the roller, while the mold must have nanometer scale features. Furthermore, it is typically beneficial to have a roller of a large diameter, as this can mitigate the distorting effects of curvature on the imprinted features. However, with a large diameter roller, it is even more difficult and expensive to obtain nanoscale-featured sheet molds of sufficient size for wrapping purposes. It has been noted that, for nanoscale work, mold fabrication remains the most expensive consumable in roll-to-roll nanoimprinting per unit area.

Seamless roller molds have been proposed to address some of the problems associated with wrapping a sheet mold. Such seamless roller molds generally rely on beam writing techniques for fabrication of nanoscale features directly on the surface of the roller (as opposed to wrapping techniques). However, these techniques tend to be very slow and therefore not desirable for large diameter roller molds. Even for research and development purposes where relatively smaller molds may be employed, seamless molds may be undesirable due to the high fabrication and duplication costs. Also, there are a number of applications where a continuous imprinting process is important to achieve high throughput, but where a seamless, continuously patterned roller mold may not necessarily be required. For example, hard disk media or data storage applications may benefit from high throughput using

a roll-to-roll process, but can be imprinted with a discrete mold, making a seamless, continuously patterned roller mold unnecessary.

Furthermore, since there are rotating parts involved in all roll-to-roll processing, there may be wear at joints and between rotating parts. One joint of particular concern are rotary joints used in core clamps where the mating faces are commonly composed of silicon carbide or tungsten carbide. These mating faces usually need to be lapped and polished so that they can form a mechanical seal when the two faces mate. However, these mating faces abrade against each other and may thus eventually wear off, causing a lubricant leak. Another problem with the abrasion is that it can generate particles, which can contaminate the lubricant or the external cleanroom environment. Contact sliding may also have speed limitations over which heat becomes intolerable and may greatly increase the wear rate.

Thus, there exists a need to provide an imprinting apparatus and method that seeks to address at least some of the above problems.

SUMMARY

As disclosed herein, there is provided an imprinting apparatus comprising:

- releasing means for releasing a feed material;
- an imprint drum comprising a rotatable inner member, and an outer member releasably mounted to the inner member and configured to engage with a first surface of the feed material for forming a plurality of structures adjacent to said first surface; and
- collecting means for collecting the feed material together with the formed structures;

wherein the outer member has an engagement surface capable of accommodating at least one sheet mold, the at least one sheet mold engaging with the first surface of the feed material for forming the respective structures.

In accordance with a first aspect, there is provided an imprinting apparatus comprising:

releasing means for releasing a feed material having a first surface and a second surface;

5 peeling means for removing a protective layer from at least one of the first surface and the second surface of the feed material;

an imprint drum comprising a rotatable inner member, and an outer member releasably mounted to the inner member and configured to engage with the first surface of the feed material for forming a plurality of structures adjacent to said first
10 surface; and

collecting means for collecting the feed material together with the formed structures;

wherein the outer member has an engagement surface capable of accommodating at least one sheet mold, the at least one sheet mold engaging with
15 the first surface of the feed material for forming the respective structures.

The engagement surface may have at least one slot for receiving at least one detachable part having the respective sheet mold mounted thereon.

5 The at least one sheet mold may be directly mounted to the engagement surface using one of a group consisting of mechanical fastening, gluing and magnetic attachment.

10 The releasing means and collecting means may each comprise a roller mounted on a respective air bearing rotary joint.

The feed material may be in a continuous sheet from the releasing means to the collecting means, and the apparatus may further comprise guiding means for guiding the feed material from the releasing means to the collecting means.

15 The guiding means may comprise:
a plurality of rollers configured to contact a second surface of the feed material, and
at least one sensor for determining a tension in the feed material for adjusting a speed of the inner member, thereby respective speeds of the releasing and
20 collecting means.

25 The apparatus may further comprise peeling means for removing a protective layer from at least one of the first surface and the second surface of the feed material.

The apparatus may further comprise a backing roller configured to contact the second surface of the feed material when each sheet mold engages with the first surface for forming the respective structures.

30 The formed structures may be detachably disposed on the first surface.

The apparatus may further comprise dispensing means configured to dispense a ultra violet (UV) curable material directly onto the at least one sheet mold for forming the respective structures.

The dispensing means may comprise an inkjet dispense head configured to dispense a plurality of drops of the UV curable material onto the sheet mold based on a respective pattern of the structures.

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The apparatus may further comprise controlling means for controlling a volume of the UV curable material at a predetermined position on the respective sheet mold.

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The apparatus may further comprise at least one UV light source for curing the formed structures disposed on the first surface of the feed material.

The formed structures may be integral with the feed material.

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The feed material may comprise a thermoplastic polymer, and the at least one sheet mold may be configured to imprint the respective structures directly onto the thermoplastic polymer.

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The apparatus may further comprise a heating source disposed in the inner member of the imprint drum for heating the at least one sheet mold to a temperature above a glass transition temperature of the thermoplastic polymer.

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The apparatus may further comprise a heating source disposed in each detachable part for heating the respective sheet mold mounted thereon to a temperature above a glass transition temperature of the thermoplastic polymer.

The formed structures may be micro-scale or nano-scale structures.

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The at least one sheet mold may be fabricated using a material from a group consisting of nickel, NiCo (nickel, cobalt alloy), fluoropolymers and plastics.

The at least one sheet mold may comprise a hybrid mold having a hard coating layer on top of a conformal backing layer.

The engagement surface may have a plurality of sheet molds attached thereto, and each of the plurality of sheet molds may have respective feature resolution and design.

5 As disclosed herein, there is provided an imprinting method comprising the step of:

 providing an imprint drum comprising a rotatable inner member, and an outer member releasably mounted to the inner member, wherein the outer member has an engagement surface capable of accommodating at least one sheet mold;

10 releasing a feed material;

 engaging the at least one sheet mold with a first surface of the feed material for forming a plurality of respective structures adjacent to said first surface; and
 collecting the feed material together with the formed structures.

15 In accordance with a second aspect, there is provided an imprinting method comprising the step of:

 providing an imprint drum comprising a rotatable inner member, and an outer member releasably mounted to the inner member, wherein the outer member has an engagement surface capable of accommodating at least one sheet mold;

20 releasing a feed material having a first surface and a second surface;

 removing a protective layer from at least one of the first surface and the second surface of the feed material;

 engaging the at least one sheet mold with the first surface of the feed material for forming a plurality of respective structures adjacent to said first surface;

25 and

 collecting the feed material together with the formed structures.

As disclosed herein, there is provided a method for fabricating an imprint drum for an imprinting apparatus, the method comprising the steps of:

30 providing an outer member having an engagement surface capable of accommodating at least one sheet mold, the at least one sheet mold being configured to engage with a first surface of a feed material for forming respective structures; and

mounting the outer member to a rotatable inner member.

In accordance with a third aspect, there is provided a method for fabricating an imprint drum for an imprinting apparatus, the method comprising the steps of:

- 5 providing an outer member having an engagement surface comprising at least one slot for receiving at least one detachable part capable of accommodating at least one sheet mold, the at least one sheet mold being configured to engage with a first surface of a feed material comprising a thermoplastic polymer for forming respective structures;
- 10 mounting the outer member to a rotatable inner member; and
- installing a heating source in the at least one detachable part for heating the at least one sheet mold when present, to a temperature above a glass transition temperature of the thermoplastic polymer.

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BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of

20 example only, and in conjunction with the drawings, in which:

Figure 1a shows a schematic diagram illustrating a UV roll-to-roll nanoimprinting system according to the prior art.

Figure 1b shows a schematic diagram illustrating a thermal roll-to-roll imprinting system according to the prior art.

Figure 2a shows a schematic diagram illustrating an imprinting apparatus
5 according to an example embodiment.

Figure 2b shows an image of an example implementation of the imprinting apparatus of Figure 2a.

10 Figure 3a shows a schematic diagram illustrating a shaft mounting for the rewinding module according to an example embodiment.

Figure 3b shows an enlarged view of a portion of Figure 3a.

15 Figure 3c shows an enlarged view of another portion of Figure 3a.

Figure 3d shows an alternate view of Figure 3c.

20 Figure 3e shows an enlarged view of a portion of Figure 3d.

Figure 4 shows a schematic diagram illustrating a clamping mechanism for the winder for collecting the protective materials from the plastic web according to an example embodiment.

25 Figure 5 shows schematic diagrams illustrating sectional views of the guide rollers including the load cells mounted thereon respectively.

30 Figure 6a shows a plan view illustrating the peeling means according to an example embodiment.

Figure 6b shows a perspective view of the peeling means of Figure 6a.

Figure 7a shows a schematic diagram illustrating a sectional view of the imprint drum according to an example embodiment.

Figure 7b shows an image of an example implementation of the imprint drum of Figure 7a.

5 Figures 8a-8d show schematic diagrams illustrating clamping a sheet mold according to an example embodiment.

Figures 9a-9d show schematic diagrams illustrating mounting the clamped sheet mold to a corresponding part according to an example embodiment.

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Figure 10 shows an image of an inkjet dispensing head according to an example implementation.

Figures 11a-d show schematic diagrams illustrating a UV roll-to-roll nanoimprinting process utilizing a continuous flow of a UV curable resin according to an example embodiment.

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Figures 12a-e show schematic diagrams illustrating a UV roll-to-roll nanoimprinting process utilizing a drop-on demand deposition of a UV curable resin according to an alternate embodiment.

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Figure 13 show a schematic diagram illustrating a press roller set according to an example embodiment.

25 Figure 14 show a schematic diagram illustrating the results of the pressing action by the imprint drum and press rollers on the plastic web according to an example embodiment.

Figure 15a shows a schematic diagram illustrating a UV lamp assembly suitable for curing the resin according to an example embodiment.

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Figure 15b shows a perspective view of the UV lamp assembly of Figure 15a.

Figure 16 shows a schematic diagram illustrating use of a central heating element in the imprint drum according to an example embodiment.

Figure 17 shows a schematic diagram illustrating use of an individual heating element in the imprint drum according to an alternate embodiment.

Figure 18 shows a flow chart 1800 illustrating an imprinting method according to an example embodiment.

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DETAILED DESCRIPTION

Figure 2a shows a schematic diagram illustrating an imprinting apparatus 200 according to an example embodiment. Figure 2b shows an image of an example implementation of the imprinting apparatus 200 of Figure 2a. The imprinting apparatus 200 includes releasing means, in the form of an unwinding module 202, for releasing, e.g. rotatably, a feed material 201 (hereinafter interchangeably referred to as plastic web 201); an imprint drum 204 for forming a plurality of structures (not shown) adjacent to a first surface 203 of the feed material 201; and collecting means, in the form of a rewinding module 206, for collecting, e.g. rotatably, the feed material 201 together with the formed structures. In a preferred embodiment, the imprint drum 204 includes a rotatable inner member 702, and an outer member 704 releasably mounted to the inner member 702, as will be described in detail below with respect to Figure 7a. Moreover, the outer member 704 has an engagement surface 734 (Figure 7a-b) capable of accommodating at least one sheet mold 802 (Figure 8). During operation, the at least one sheet mold 802 engages with the first surface 203 of the feed material 201 for forming the respective structures.

In some implementations, smooth movement of the feed material or web 201 with a constant speed may be determined by the rotational speed (e.g. measured in rounds per minute (RPM)) of the imprint drum 204. The unwinding and rewinding modules 202, 206 may employ "active slave" detection to check a web tension at their respective sections in real-time, and respond with appropriate rotational speeds

to maintain a preset web tension. Typically, a roll of the plastic web 201 may be loaded to a shaft of the unwinding module 202 which may be equipped with a quick release core clamp, as will be discussed below with respect to Figures 3a-3e. The plastic web 201 is then guided by various rollers 208a-208e, 220a-b, including the imprint drum 204, before finally reaching the rewinding module 206. The rewinding module 206 may also have a shaft with a quick release core clamp of exactly the same design as the unwinding module 202. In preferred implementations, the core clamping, unwinding and rewinding, etc. of the feed material 201 may be controlled by software-automated mechanisms.

For example, sensing means, in the form of load cells 510a, 510b (Figure 5), are employed in the rollers 220a, 220b respectively to measure web tension "on the fly". With reference to Figure 5, the load acting on the surface of the respective roller 220a, 220b can be totalled, since the angle of the web 201 around the respective roller shell 502a, 502b is known. Thus, web tension can be calculated precisely. The tension control logic can be a proportional-integral-derivative feedback loop with a quick response.

As shown in Figures 2a and 2b, the imprinting apparatus 200 may further include a peeling module 210 for removing protective materials from the plastic feed. For example, the peeling module 210 includes a first winder 212 and first set of weight rollers 214 for removing a protective layer from the first surface 203, and a second winder 216 and a second set of weight rollers 218 for removing a protective layer from a second surface 205 of the plastic web 201. In addition, the imprinting system 200 may include cleaning means 222 for cleaning the plastic web 201 before imprinting, and a press roller set 224 to assist in pressing the plastic web 201 against the imprint drum 204. In the embodiment shown in Figures 2a and 2b, the imprinting apparatus 200 is a UV roll-to-roll imprinting apparatus. Dispensing means, in the form of a print head 226, is used to dispense a UV curable material on the sheet mold 802 (Figure 8) from which the structures may be formed. In addition, a UV light source, in the form of UV lamps 228a, 228b, may be used to cure the formed structures. It will be appreciated that in other embodiments that do not utilize UV curing, the dispensing means and the UV light source may be removed.

Figure 3a shows a schematic diagram illustrating a shaft mounting mechanism 300 for the rewinding module 206 with a quick release core clamp according to an example embodiment. The roll of the plastic web 201 may be clamped by an inner surface of its hollow core tube.

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With reference to Figure 3a, clamping is essentially achieved by the sliding of two slanted faces. For example, an expansion blade 302 may slide on an expansion rod 304 where both components have slanted faces in contact. The expansion blade 302 may be secured axially but allowed to move in a radially outward direction. The expansion rod 304 may be guided and can only move in an axial direction. Air may be supplied from an air bearing rotary joint 306, which goes through a hole drilled to the centre of the shaft 308 to actuate a piston 310. The piston 310 pushes the expansion rod 304 and the expansion blade 302 contracts. When a new reel is inserted onto the shaft 308, the air supply is cut off and the spring 312 pushes back the expansion rod 304 and expands the expansion blade 302 to clamp the hollow core. The shaft 308 is coupled to an actuating means, in the form of a servo motor 301, via coupling 303. In addition, angular contact bearing 305 and ball bearing 307 facilitate rotational movement by the shaft 308 relative to the air bearing rotary joint 306. Metal bushing 316a, 316b are placed between the shaft 308 and the expansion rod 304. Figure 3b shows an enlarged view of a portion of Figure 3a illustrating the piston 310 and the spring 312, together with a floating air inlet 314, a metal bushing 316a and a wear ring 318.

Figure 3c shows an enlarged view of a portion of Figure 3a illustrating a rod expansion mechanism utilizing compressed air according to an example embodiment. Figure 3d shows an alternate view of Figure 3c. Figure 3e shows an enlarged view of an air bearing portion 340 of Figure 3d. In order to automate clamping and unclamping of the core clamp without causing wear and particulation at the mating faces, air bearing is used in an example implementation. Here, the air bearing rotary joint (ABRJ's) 306 utilizes compressed air, where the compressed air is fed in via the main shaft 308 while the shaft 308 is rotating. Furthermore, the clamping system used in the example embodiments is self-centering (concentric), which may be useful in maintaining a precise web tension.

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As shown in Figures 3c-3d, the ABRJ 306 in the example embodiments includes 3 compressed air inlets 320, 322, 324. The middle inlet 320 may be used to supply compressed air to actuators, e.g. piston 310, while the other two inlets 322, 324 are used to supply compressed air to the air bearing 326. A groove, e.g. 323, is formed in the ABRJ 306 for each of the respective inlets 320, 322, 324. There are four O-ring seals 328a-d between the interface of air bearing 326 and the housing 330 in one implementation. The O-rings 328a-d isolate and seal the three different compressed air supplies passages at the interface so they always remain isolated. Typically, there is a floating gap 332 at the interface between the air bearing 326 and the housing 330, as shown more clearly in Figure 3d. The gap 332, which is about 0.2-0.3 mm, may cater for concentric tolerance of the air bearing 326. Since the O-rings 328a-d are elastic, a minor concentric inaccuracy can be tolerated. A locating pin 334 may be disposed in the housing 330 to set the air bearing 326 in the housing 330, to prevent axial and rotary movement.

With reference to Figure 3e, compressed air enters at the midpoint of the air gap 336, a gap of about 4 - 6 microns (μm), forming a pressurized air film that separates the rotating shaft 308 and the inner wall of an air bearing 337. Typically, the rotary air bearing 337 in the example embodiments can sustain a force equal to the rectangular area of the diameter of the shaft 308 and the length of the air gap 336 multiplied by the air pressure. Compressed air that enters the air gap 336 may eventually reach air escape passages, e.g. 338, at both ends of the air gap 336.

Figure 4 shows a schematic diagram illustrating a clamping mechanism 400 for the winder 212 or 216 (Figure 2a) for collecting the materials from the plastic web 201 (Figure 2) according to an example embodiment. A separate mechanism from that shown in Figures 3a-3e is used in the clamping of the hollow core of the roll of the protective material. As shown in Figure 4, the mechanism 400 uses an external pneumatic cylinder 402 to push and contract the expansion blade 404 via a spring 403 and a pull rod 410. A metal bushing 412 is placed between the pull rod 410 and a shaft 408. The rotation of the shaft 408 is facilitated by a set of angular contact bearing 405 and ball bearing 407. The basic working principles of the mechanisms 300 (Figure 3a) and 400 are the same; the main difference is that the rewinding (or

unwinding) module 202, 206 (Figure 2a) may allow direct coupling to the motor while the winder 212, 216 may require a timing pulley 406.

Figure 5 show schematic diagrams illustrating sectional views of the guide rollers 220a, 220b (Figure 2a) including the load cells 510a, 510b mounted thereon respectively. The guide rollers 220a, 220b includes respective rotatable roller shells 502a, 502b that are in contact with the plastic web. Each of the guide rollers 220a, 220b is clamped using a respective self-centering expansion clamp 504a, 504b. Further, each of the load cells 510a, 510b may be coupled to the respective guide roller 220a, 220b using fastening means inserted in a respective threaded hole 506a, 506b.

Figure 6a shows a plan view illustrating the peeling means 210 (Figure 2) according to an example embodiment. Figure 6b shows a perspective view of the peeling means 210 of Figure 6a. It will be appreciated that the plastic web 201 (Figure 1) generally comes with protective plastic cover layers 602a, 602b on the front and backside in order to protect against scratches, particles and other contaminants. In the example embodiments, prior to being fed into the imprinting module 204, these protective layers 602a, 602b are removed. The peeling means 210 utilizes two identical sub-systems 610a, 610b each including a winder 212, 216 and a weight roller 214, 218 (Figure 2a), to wind, tension and collect a respective protective layer 602a, 602b from each side of the web 201. The weight rollers 214, 218 shown in Figures 6a, 6b may be idler rollers mounted on a linear bearing guidance system 606 in one implementation. Each weight roller 214, 218 can move up and down freely within a certain span 604a, 604b. The protective layers 602a, 602b wrap around the respective weight rollers 214, 218 such that, when the winders 212, 216 rotate, the slack from the respective protective layers 602a, 602b may be tensioned by the weight of the weight rollers 214, 218. The sub-systems 610a, 610b may operate independently of each other. When the weight roller 214, 218 reaches the lower end of the span 604a, 604b, a first sensor activates the motor of the winder 212, 216 to wind the respective protective layer 602a, 602b onto the respective core. During winding, the weight roller 214, 218 may move upwards until it reaches the upper end of the span 604a, 604b and triggers a second sensor to stop the motor of the winder 212, 216. The weight of the weight rollers 214, 218 can

be adjusted by varying the pressure of an air cylinder counter-balancing the weight of the roller. The shafts of the winders 212, 216 are also equipped with quick-release core clamps.

5 Figure 7a shows a schematic diagram illustrating a sectional view of the imprint drum 204 (Figure 2) according to an example embodiment. Figure 7b shows an image of an example implementation of the imprint drum 204 of Figure 7a. As described above, the imprint drum 204 has a rotatable inner member 702 and an outer member 704 releasably mounted to the inner member 702. With reference to
10 Figure 7a, the imprint drum 204 also includes a main support shaft 706 where the inner member 702 rotates on. The outer member 704 may be secured to the inner member 702 by a tapered face 708 on one side and another split taper ring 710 on the opposing side. This setup may enable easy removal of the outer member 704, e.g. when the outer member 704 is replaced by one of a different size. In other
15 words, the size of the imprint drum 204 may be quickly adjusted by replacing an existing outer member 704 and mounting a suitably-sized outer member 704. The imprint drum 204 may rotate on bearings 712, 714 preloaded with a spring 716 to eliminate the axial play of the bearings 712, 714. One end 724 of the driving shaft 706 may be coupled, e.g. using coupling 718, to a servo motor 720 with a gear
20 reducer 722, and the other end 726 may be coupled to the outer member 704. Typically, the imprint drum 204 is configured to rotate at a constant speed. The imprint drum 204 may also include a main support 728 and a bearing spacer 730 as shown in Figure 7a. In some embodiments, dispensing means, e.g. in the form of the print head 226 (Figures 2a-b) may be mounted adjacent the imprint drum 204.

25 As illustrated more clearly in Figure 7b, in some embodiments, the outer member 704 may have at least one slot 732, typically multiple slots 732a-b, where a respective sheet mold 802 (Figure 8) can be mounted (e.g. a nickel electroformed sheet mold). Each slot 732a-b can receive a corresponding stainless steel part 902
30 (Figure 9) that is configured to precisely fit into the slot 732a-b in order to create a continuous, smooth drum engagement surface 734. In a preferred embodiment, a plurality of sheet molds 802, each having respective feature resolution, design, etc., can thus be attached to the engagement surface 734.

The aforementioned parts are also configured for mounting the respective sheet mold 802 under tension, such that the sheet mold 802 can be mounted on the imprint drum 204 as if it were wrapped on the drum 204 while only occupying a portion of the drum engagement surface 734 (as opposed to being wrapped around the entire drum engagement surface 734). Typically, the sheet mold 802 is mounted onto the corresponding mounting part 902, which is then mounted to a respective slot 732a-b, as will be described in detail below with respect to Figures 8a-d and 9a-d. This may be advantageous for nanoscale work (<100 nm) where mold master fabrication becomes prohibitively expensive and it is difficult (or extraordinarily expensive) to obtain molds of a size large enough to wrap around the imprint drum 204. However, it would be appreciated that in alternate embodiments, the slots 732a-b can be removed and replaced with another outer member 704 for the purposes of mounting a large sheet mold 802 around the entire imprint drum 204. This alternate configuration may cater for technological advances which may lead to an inexpensive manufacture of large area, nanoscale sheet molds, as well as seamless (patterned) imprint drums.

Figures 8a-8d and 9a-9d show schematic diagrams illustrating mounting a sheet mold 802 to a corresponding part 902 according to an example embodiment. Typically, the sheet mold 802 (e.g. a nickel sheet mold) has a thickness in the range from 0.1~0.3 mm. It will be appreciated that in alternate embodiments, the sheet mold 802 may be made from a different material, including but not limited to NiCo (nickel, cobalt alloy), or fluoropolymers (ETFE, PTFE, Teflon), or ordinary plastics such as polycarbonate, PMMA, PET, etc. In further embodiments, the sheet mold 802 may be a hybrid mold containing a hard textured surface composed of, for example a silicon dioxide, quartz, metal, or other hard coating or layer on top of a conformal backing layer formed from a material such as polydimethylsiloxane (PDMS), or other polymer or elastomer. In order to tension such a thin sheet, both ends of the stainless steel part 902 are reinforced with clamps 804. As shown in Figures 8a-8d, each end of the nickel sheet mold 802 is gripped and sandwiched by a separate metal bar 806, forming a clamp on each side that is secured by screws 808. For a permanent mount, epoxy glue can also be applied between the metal bars 806 and the nickel mold 802, providing an even load distribution when tensioning. As shown in Figures 9a-9d, the reinforced nickel mold 802 is then secured and tensioned onto the

corresponding part 902 (also referred to as a backing plate) with an arc parameter exactly equal to that of the imprint drum 204 (Figure 2a). Two filler bars 904a, 904b (Figures 9c-9d) may also be secured on both sides of the part 902 after the latter is slot mounted on the outer member 704 (Figure 7a) of imprint drum 204. These filler bars
5 904a, 904b may help to cover and restore the part 902 to full arc, to provide a continuous engagement surface 734 (Figure 7a).

In alternate embodiments, the sheet mold 802 (Figure 8a) may be mounted to the imprint drum 204 (Figure 7a) by mechanically fastening the sheet mold 802
10 directly to engagement surface 734 (Figures 7a-b) of the imprint drum 204, without carving slots 732a-b (Figure 7b) in outer member 704. For example, the respective mold or molds 802 may be directly fastened, e.g. using screws, to the outer member 704 with filler bars, instead of mounting the mold 802 to a stainless steel part 902 (Figure 9a) that is then slotted into the drum 204.

In further alternate embodiments, the sheet mold 802 may be mounted by gluing or magnetically attaching the mold 802 to the engagement surface 734 (Figure 7a-b) of the imprint drum 204, where the area of the mold 802 is small enough such that multiple molds may be (but not necessarily) mounted on the
20 imprint drum 204 in this manner. For example, for magnetic attachment, the imprint drum 204 may be made from a ferromagnetic material such as iron, cobalt, nickel, alloys thereof, alloys of copper, alloys of manganese, iron oxides and chromium oxides. These materials can be spontaneously magnetized for the attachment of metallic molds that are attracted to ferromagnetic materials.

It will be appreciated that even in the alternate embodiments, an imprint drum 204 having an inner member 702 and an outer member 704 may still be used. In cases where multiple molds 802, each having its own resolution and design, are used on one imprint drum 204, the mold mounting as described above can be
30 carried out for each of the molds. The outer member 704 can be removed and replaced with a different outer member containing different mounted parts 902, different mounted molds 802, or molds 802 mounted using a different mounting method.

Figure 10 shows an image of an inkjet dispense head 1000 (i.e. print head 226 shown in Figure 2a) according to an example implementation. In embodiments using UV curing, a UV curable resin is dispensed from the inkjet dispense head 1000 directly onto the mounted nickel sheet mold 802 (Figure 8a). This may be an advantageous arrangement compared to the commonly accepted approach of dispensing on the web 201 (Figure 2). This is because the dispensed droplets on the web 201 need to be precisely aligned and timed to join with the mold 802 at exactly the right moment when the web 201 and mold 802 are pressed together by the pressure rollers 1302a-b (Figure 13). It may be much easier to fix the dispense head 1000 over the mold track such that it may be laterally pre-aligned relative to the mold, and to integrate a timing mechanism or sensor with the dispense head 1000 to time the dispensing with the arrival of the mold 802 (or for continuous mold, simply dispense continuously).

Figures 11a-d show schematic diagrams illustrating a UV roll-to-roll nanoimprinting process utilizing a continuous flow of a UV curable resin 1102 according to an example embodiment. As shown in Figure 11a, in Step 1, the resin 1102, which is contained in a container 1104 of the dispense head 1000 (Figure 10) is deposited on a mold 1106 mounted on an imprint drum 1108 and having a plurality of mold cavities 1110 and mold protrusions 1112. As shown in Figure 11b, in Step 2, a web 1114 is brought into contact with the deposited resin for pressing against the resin. As shown in Figure 11c, in Step 3, after the resin is spread against the web 1114, e.g. by pressure rollers 1302a-b (Figure 13), the resin is polymerized by UV radiation generated by a UV light source. As shown in Figure 11d, in Step 4, the solidified structures 1118 adjacent to (e.g. attached to) the surface of the web 1114 are removed from the mold 1106. Any excess resin 1116 may be removed before Step 4.

In an example implementation, liquid dispensing of the UV curable resin 1102 may be achieved by a continuous dispensing of resin droplets on the mold 1106 using a print head 1000 fabricated by Solves Innovative Technology Pte Ltd of Singapore, utilizing 128 nozzles arranged in a 65 mm width line. The nozzles may be purchased from FUJIFILM Dimatix, Inc. of Santa Clara, USA. The resin 1102 appears as 128 lines of droplets deposited on the sheet mold 1106 while the latter

travels beneath the print head 1000. The volume of a single droplet may be only about 10 picoliters (pl) (i.e. a sphere of diameter 13.37 micron). In order to control the shape of the dispensed area on the mold 1106, 1-bit (black and white) images may be loaded into the dispensing software prior to actual dispensing. These
5 images define when and where the dispense nozzles may fire. For example, the software may scan from left to right across the image, and when a black region of the image is detected, the corresponding nozzles in the dispense head 1000 may be fired, and vice-versa for white regions.

10 Figures 12a-e show schematic diagrams illustrating a UV roll-to-roll nanoimprinting process utilizing a drop-on demand deposition of a UV curable resin 1202 according to an alternate embodiment. As shown in Figure 12a, in Step 1, the resin 1202, which is contained in a container 1204 of the dispense head 1000 (Figure 10) is deposited on a mold 1206 mounted on an imprint drum 1208 and
15 having a plurality of mold cavities 1210 and mold protrusions 1212. As illustrated more clearly in Figure 12b, individual drops of the resin 1202 are deposited. In preferred implementations, the number and volume of the drops may be controlled based on e.g. the pattern of the structures to be formed. As shown in Figure 12b, in Step 2, a web 1214 is brought into contact with the deposited drops for pressing
20 against the drops. As shown in Figure 12c, in Step 3, after the resin is spread against the web 1214, e.g. by pressure rollers 1302a-b (Figure 13), the resin is polymerized by UV radiation generated by a UV light source. As shown in Figure 12d, in Step 4, the solidified structures 1218 attached to the surface of the web 1214 are removed from the mold 1106. In this embodiment, there is typically little excess
25 resin as the dispensed amount can be accurately controlled.

In other words, drop-level control may be achieved by incorporating a drop-on-demand dispensing system in the imprinting apparatus 200 (Figure 2a). This system may allow fine adjustment of local dispensed volume to place more resin
30 drops e.g. where larger or more numerous mold cavities exist, thus planarizing the residual layer, increasing fidelity, uniformity and reducing defects. The drop-on-demand dispensing system of the example embodiments may have nozzle-level control over the number of drops dispensed from a given nozzle via appropriate driver circuitry and software.

Using inkjet dispensing in the example embodiments may be advantageous in terms of resin conservation. It would be appreciated that the resin is one of the most expensive components of the manufacturing line from an absolute cost input point of view as it is a consumable that is not re-used. Conventional inkjet systems, for comparison, typically use only 0.1-1.0% of the resin consumed by traditional spin-coating techniques, which typically spin-off >99% of the resin.

Figure 13 show a schematic diagram illustrating a press roller set 224 (Figure 2a) according to an example embodiment. As described above, after deposition, the mold 1106, 1206 (Figures 11a, 12a) with deposited resin is then pressed against the plastic web 201 (Figure 2a) (which is fed in by the web unwinding module 202 (Figure 2)) by the pressure roller set 224. For example, the press roller set 224 includes two polyurethane rollers 1302a, 1302b with shore hardness of about 60~80. Each roller 1302a, 1302b may be actuated by a respective low friction pneumatic cylinder 1304a, 1304b, where the pressure of each cylinder 1304a, 1304b can be varied to adjust to the web tension tracking. The principal function of these rollers 1302a, 1302b is to squeeze and spread the UV curable resin between the web and the mold, which may assist with the filling of the mold cavities, and help to reduce or eliminate air bubble trapping.

Figure 14 shows a schematic diagram illustrating the results of the pressing action by the imprint drum 1402 and press rollers 1404a, 1404b on the plastic web 1406 according to an example embodiment. Here, the sheet mold 1407 is mounted on a respective mold slot 1408. After the mold 1407 engages with the web 1406, structures 1410, 1412 are formed and disposed on a surface 1414 of the web 1406 based on the respective mold 1407.

The next step in the example embodiment using UV curable resin is to polymerize and solidify the resin. Figure 15a shows a schematic diagram illustrating a UV lamp 1500 assembly suitable for curing the resin according to an example embodiment. Figure 15b shows a perspective view of the UV lamp assembly 1500 of Figure 15a. In some implementations, two Mercury UV lamp assemblies 1500 (i.e. UV light sources 228a, 228b (Figure 2a)) are installed under the imprint drum 204

(Figure 2a) to cure the resin. Each UV lamp assembly 1500 includes a UV lamp 1502 with a power rating of about 300 watts per inch (W/in) or 2.4kW in embodiments where the arc length is 8 inches. The lamp 1502 may be installed at the foci of a parabolic reflector 1504. Since the UV lamp 1502 may generate a lot of heat, a "cold mirror" 1506 may be used as a band pass filter, reflecting only the UV wavelength range from 250~400 nm onto the resin/web assembly, while the remaining radiation passes through the cold mirror 1506 and is dumped to a heat sink 1508. The cold mirror 1506 may be positioned at 45° with respect to the irradiation from the lamp 1502, which is directionally concentrated by the back-end parabolic reflector 1504. As illustrated in Figure 15b, the lamp 1502 may be disposed in housing 1510 which is insulated with a heat-resistant material. Air is sucked into the housing 1510 via openings 1512, 1514 in the housing wall to cool the lamp 1502 as well as the heat sink 1508. In addition, since the UV lamp 1502 cannot be turned on or off instantly, the lamp 1502 normally remains turned on during operation, and a shutter 1516 is installed so that it can block the UV rays when necessary. For example, the shutter 1516 may be controlled by a rotary actuator 1518 for opening or closing a UV radiation window 1520, as shown in Figure 15b.

With reference to Figure 2a, once the resin is fully cured by the UV light source 228a, 228b (UV lamp assembly 1500), the imprint drum 204 is rotated until separation with the web 201 takes place. Following that, the imprinted web together with the formed structures is re-wound by the web rewinding module 206. The described apparatus can handle a variety of plastic web feedstock, including but not limited to polycarbonate (PC) and polyethylene terephthalate (PET), and various resin chemistries so long as the viscosity of the resin remains below certain limits (~30 mPa·s).

In an alternate embodiment called thermal roll-to-roll nanoimprinting, the UV curable resin is not required, and the structures may be formed directly into the plastic web. In this thermal roll-to-roll nanoimprinting embodiment, the apparatus 200 (Figure 2a) may have at least one heating element incorporated into the imprint drum 204 (Figure 2a) in order to raise the temperature of the mold 802 (Figure 8a)

above the glass transition temperature of the thermoplastic web material being used, such that it can pattern the thermoplastic web or film directly.

Figure 16 shows a schematic diagram illustrating use of a heating element 5 1602 in the imprint drum 1604 according to an example embodiment. Here, the heating element 1602 can be installed in the core or center of the imprint drum 1604. A sheet mold 1606 is mounted onto a mold mounting part 1608, which is then mounted to a respective slot 1609 on the engagement surface 1610 of the imprint drum 1604. As a result of the engagement of the mold 1606 with the thermoplastic 10 web 1612, structures 1614 are formed on the web surface 1616, e.g. integral with the web 1612.

Figure 17 shows a schematic diagram illustrating use of a heating element 1702 in the imprint drum 1704 according to an alternate embodiment. Here, the 15 heating element 1702 is installed in the mold mounting part 1708 beneath the tensioned mold 1706 itself. The mold mounting part 1708 is mounted onto a respective slot 1709 on the engagement surface 1710 of the imprint drum 1704. As a result of the engagement of the mold 1706 with the thermoplastic web 1712, structures 1714 are formed adjacent to the web surface 1716, e.g. integral with the 20 web 1712. In this embodiment, multiple heating elements 1702 may be required if multiple slots 1709 are formed into the imprint drum 1704 for the respective parts 1708, which may increase complexity.

For fast heating and cooling it is generally preferable to place the heating 25 element 1702 in the mold mounting part 1708 and insulate the mold mounting part 1702 from the rest of the imprint drum 1708, e.g. with an insulating material, as less heating may be required to reach the set temperature at the mold surface. On the other hand, for better temperature uniformity it is preferable to place the heating element 1702 in the core of the imprint drum 1704 and to ensure the imprint drum 30 1704 is constructed of relatively dense materials with good heat conductivity (e.g. copper, aluminum).

The example embodiments as described may allow mounting multiple small molds, which can be fabricated from a range of materials such as metals, alloys,

plastics, fluoropolymers etc. Alternatively, the molds may be hybrid molds containing a hard textured surface composed of, for example a silicon dioxide, quartz, metal, or other hard coating or layer on top of a conformal backing layer formed from a material such as polydimethylsiloxane (PDMS), or other polymer or elastomer. Moreover, the molds can be of different resolutions and designs, on a single imprint drum. This may help to get around the fact that molds with features of nanoscale dimensions are very expensive to manufacture and tend to be of small size in order to reduce cost. In one implementation, the UV roll-to-roll nanoimprinting apparatus of the example embodiments can mount up to six molds, three of 160 x 75 mm size and three of 105 x 75 mm size.

In addition, the inkjet dispensing unit and its mode of operation have not been demonstrated in UV roll-to-roll nanoimprinting. Because specialized UV curable resins for nanoimprinting tend to be expensive to manufacture, it may be useful to conserve the resin during the roll-to-roll nanoimprinting process. In the example embodiments, the inkjet dispensing unit can place resin droplets exclusively on the patterned area of the mold, and therefore can reduce resin wastage compared to gravure coating approaches, which coat resin over the entire web.

Moreover, dispensing on the mold according to the example embodiments may be advantageous compared to dispensing on the web, despite the fact that dispensing on the web is the commonly accepted approach in UV roll-to-roll nanoimprinting. In the approach of the example embodiments, the inkjet dispensing head can be aligned and fixed in place over the mounted sheet molds, such that the resin is dispensed over precisely the correct length and width to fully cover the mold with no misalignment and no underfilled regions. On the other hand, if the resin were instead dispensed onto the web, the web would have to be aligned properly so that the resin would contact the mold at precisely the right moment when the web and the mold are brought in contact. It is generally easier to calibrate and align the dispensing head with the mold directly, and eliminate the need to align the web.

The use of an air bearing as a rotary joint in the example embodiments may be advantageous in that it is a non-contact sealing compared to other mechanical

seals that require mating parts. The life of an air bearing may be substantially limitless, and it is clean, suitable for clean room use. Also, to keep the system compact, a piston may be used to actuate the clamping blades, all of which may be custom made to be assembled together, instead of using an off-the-shelf cylinder.

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Furthermore, the apparatus according to the example embodiments may have built-in flexibility in terms of imprint drum mounting because of configuration using an inner member and a releasable outer member. The outer member of the imprint drum can be removed and replaced with e.g. a different outer member, or
10 with a featureless shell for wrapping a large sheet mold around the imprint drum itself, or for mounting a seamless mold shell.

Figure 18 shows a flow chart 1800 illustrating an imprinting method according to an example embodiment. At step 1802, an imprint drum comprising a rotatable
15 inner member, and an outer member releasably mounted to the inner member, wherein the outer member has an engagement surface capable of accommodating at least one sheet mold is provided. At step 1804, a feed material is released. At step 1806, at least one sheet mold is engaged with a first surface of the feed material for forming a plurality of respective structures adjacent to said first surface.
20 At step 1808, the feed material together with the formed structures is collected.

Plastic webs with textured coatings as produced using the apparatus and method of the example embodiments may have several commercial applications, particularly in the area of anti-reflection films and coatings, brightening enhancement
25 films and coatings for displays, functional films with self-cleaning, anti-fouling surfaces, surfaces with structural color, wire-grid polarizers, bit-patterned media, mold replication, display backplanes, and many others.

It will be appreciated by a person skilled in the art that numerous variations
30 and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. An imprinting apparatus comprising:
releasing means for releasing a feed material having a first surface and a second surface;
peeling means for removing a protective layer from at least one of the first surface and the second surface of the feed material;
an imprint drum comprising a rotatable inner member, and an outer member releasably mounted to the inner member and configured to engage with the first surface of the feed material for forming a plurality of structures adjacent to said first surface; and
collecting means for collecting the feed material together with the formed structures;
wherein the outer member has an engagement surface capable of accommodating at least one sheet mold, the at least one sheet mold engaging with the first surface of the feed material for forming the respective structures.
2. The apparatus as claimed in claim 1, wherein the engagement surface has at least one slot for receiving at least one detachable part having the respective sheet mold mounted thereon.
3. The apparatus as claimed in claim 1, wherein the at least one sheet mold is directly mounted to the engagement surface using one of a group consisting of mechanical fastening, gluing and magnetic attachment.
4. The apparatus as claimed in any one of the preceding claims, wherein the releasing means and collecting means each comprises a roller mounted on a respective air bearing rotary joint.
5. The apparatus as claimed in any one of the preceding claims, wherein the feed material is in a continuous sheet from the releasing means to the collecting means, the apparatus further comprising guiding means for guiding the feed material from the releasing means to the collecting means.
6. The apparatus as claimed in claim 5, wherein the guiding means comprises:

a plurality of rollers configured to contact the second surface of the feed material, and

at least one sensor for determining a tension in the feed material for adjusting a speed of the inner member, thereby respective speeds of the releasing and collecting means.

7. The apparatus as claimed in claim 1 to 6, further comprising a backing roller configured to contact the second surface of the feed material when each sheet mold engages with the first surface for forming the respective structures.

8. The apparatus as claimed in any one of claims 1 to 7, wherein the formed structures are detachably disposed on the first surface.

9. The apparatus as claimed in claim 8, further comprising dispensing means configured to dispense a ultra violet (UV) curable material directly onto the at least one sheet mold for forming the respective structures.

10. The apparatus as claimed in claim 9, wherein the dispensing means comprises an inkjet-type dispense head configured to dispense a plurality of drops of the UV curable material onto the sheet mold based on a respective pattern of the structures.

11. The apparatus as claimed in claim 9 or 10, further comprising controlling means for controlling a volume of the UV curable material at a predetermined position on the respective sheet mold.

12. The apparatus as claimed in any one of claims 9 to 11, further comprising at least one UV light source for curing the formed structures disposed on the first surface of the feed material.

13. The apparatus as claimed in any one of claims 1 to 7, wherein the formed structures are integral with the feed material.

14. The apparatus as claimed in claim 13, wherein the feed material comprises a thermoplastic polymer, and wherein the at least one sheet mold is

configured to imprint the respective structures directly onto the thermoplastic polymer.

15. The apparatus as claimed in claim 14, further comprising a heating source disposed in the inner member of the imprint drum for heating the at least one sheet mold to a temperature above a glass transition temperature of the thermoplastic polymer.

16. The apparatus as claimed in claim 14 when dependent on claim 2, further comprising a heating source disposed in each detachable part for heating the respective sheet mold mounted thereon to a temperature above a glass transition temperature of the thermoplastic polymer.

17. The apparatus as claimed in any one of the preceding claims, wherein the formed structures are micro-scale or nano-scale structures.

18. The apparatus as claimed in any one of the preceding claims, wherein the at least one sheet mold is fabricated using a material from a group consisting of nickel, NiCo (nickel, cobalt alloy), fluoropolymers and plastics.

19. The apparatus as claimed in any one of claims 1 to 17, wherein the at least one sheet mold comprises a hybrid mold having a hard coating layer on top of a conformal backing layer.

20. The apparatus as claimed in any one of the preceding claims, wherein the engagement surface has a plurality of sheet molds attached thereto, and wherein each of the plurality of sheet molds has respective feature resolution and design.

21. An imprinting method comprising the step of:
providing an imprint drum comprising a rotatable inner member, and an outer member releasably mounted to the inner member, wherein the outer member has an engagement surface capable of accommodating at least one sheet mold;
releasing a feed material having a first surface and a second surface;
removing a protective layer from at least one of the first surface and the second surface of the feed material;

engaging the at least one sheet mold with the first surface of the feed material for forming a plurality of respective structures adjacent to said first surface; and

collecting the feed material together with the formed structures.

22. A method for fabricating an imprint drum for an imprinting apparatus, the method comprising the steps of:

providing an outer member having an engagement surface comprising at least one slot for receiving at least one detachable part capable of accommodating at least one sheet mold, the at least one sheet mold being configured to engage with a first surface of a feed material comprising a thermoplastic polymer for forming respective structures;

mounting the outer member to a rotatable inner member; and

installing a heating source in the at least one detachable part for heating the at least one sheet mold when present, to a temperature above a glass transition temperature of the thermoplastic polymer.