Imprinting Apparatus and Method

Technical Field

The present invention relates broadly to an imprinting apparatus and method.

Background

Roll-to-roll nanoimprinting is a very promising platform technology for high throughput micro- and nano-fabrication. Compared to batch mode imprinting, where each imprint is made separately on discrete substrates, roll-to-roll nanoimprinting is typically used to pattern a continuous substrate, generally a thin and flexible plastic web or feed material, with micro- to nano-scale structures. One method by which this can be performed is by UV roll-to-roll imprinting. UV roll-to-roll imprinting offers the finest feature resolution at the highest processing speed. This results from the lower viscosity of the imprint material when it is forced into the imprint mold. UV curing is then used to set the material.

FIG. 1 shows a schematic diagram illustrating a conventional UV roll-to-roll nanoimprinting system. In the system, structures are produced by depositing a UV curable resin coating, using a dispensing unit, on a plastic web or feed material and then pressing a mold with the desired patterns into the resin coating, 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, causing it to cure and form a solid, textured coating on the plastic

web upon removal of the mold. The system may also include pressure rollers and a demolding roller to assist the imprinting process, as shown in FIG. 1.

Although UV roll-to-roll imprinting has many advantages, it may also 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, but often only smaller areas are imprinted. Resin is the most expensive consumable in the production process of the imprinted product 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 feed material because the dispensed droplets on the web need to be precisely aligned and timed to join with the mold at exactly the right moment when the web and mold are pressed together by the pressure rollers.

Furthermore, because the roll-to-roll process involves the joining of surfaces in motion (e.g. the mold, the resin coating, and the feed material), defects due to trapped air can occur, especially when this joining process is carried out in normal ambient atmosphere in the absence of any vacuum or low atomic weight inert gases). This may increase the reject rate of the imprinted product, and therefore the cost of production.

In particular, there are two major challenges with regard to trapped air in UV roll-to-roll nanoimprint lithography. The first is control over air trapping (e.g. bubble formation) in the resin. The second, which is more specifically with regard to acrylic resins, is oxygen inhibition, wherein the resin fails to solidify and fully cure under UV exposure due to the

polymerization reaction being stopped by the presence of oxygen. These challenges have been extensively investigated in batch mode UV nanoimprinting. However, little has been done to specifically address these issues for UV roll-to-roll nanoimprinting, even though it is equally applicable to UV roll-to-roll nanoimprinting as it is to batch mode imprinting methods.

Air trapping during UV roll-to-roll imprinting results in defects in imprinted features such as that shown in SEM cross-section in FIG. 2A and FIG. 2B. These defects destroy the functionality of the imprint product and mechanically weaken the resin, leading to secondary defects such as pull-outs when the imprint field is separated from the mold during production. These defects also greatly reduce service lifetime of the imprinted product.

There are two known methods that may eliminate air trapping and oxygen inhibition issues. The first is to apply a vacuum to the imprint apparatus so that no air or oxygen is present during the imprint process. The second is to apply an exotic, oxygen-free gas atmosphere to the apparatus so that the trapped gas itself will more easily dissolve in the resin. Preferred gases include helium and pentafluoropropane, as the former easily dissolves in UV curable liquid resins, while the latter can undergo a phase change from a gas to a liquid under sufficient pressure (>100 kPa).

Although these approaches have been applied in batch mode nanoimprinting, they have not been reported or implemented in a UV roll-to-roll nanoimprinting system. This is mostly because the only obvious way to implement vacuum or an exotic gas environment in a roll-to-roll line is to apply it to the entire equipment chassis. Applying a vacuum to the entire equipment

chassis would be very time consuming due to the large volume of the chassis and filling the chassis with an exotic gas environment would be prohibitively expensive, particularly for helium. For both cases, the chassis would have to be converted to a glove box environment, which is not practically feasible as the equipment has moving parts and hence has to be regularly accessed in order to replace web materials, resin and other consumables. Moreover, attempts to achieve this would necessarily drive up costs and time consumption for operating the apparatus.

Thus, there exists a need to provide an imprinting apparatus and method that may at least partially ameliorate one or more of the disadvantages described above.

Summary

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

releasing means for releasing a feed material;

an imprint drum configured to engage with a first surface of the feed material for forming a plurality of structures adjacent to said first surface;

gaseous environment creation means for forming a localized exotic gas environment in between the imprint drum and the first surface of the feed material; and

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

The imprint drum may comprise a rotatable inner member, and an outer member releasably mounted to the inner member.

The outer member may have 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.

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

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.

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, the apparatus may further comprise guiding means for guiding the feed material from the releasing means to the collecting means.

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 adjusting respective speeds of the releasing and collecting means.

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.

The gaseous environment creation means may comprises a gas expulsion means and a gas containment means.

The gas expulsion means may further comprise a gas feed means and an air knife.

The gas containment means may further comprise a first surface comprising the outer surface of the air knife, a second surface comprising a first slot guard, a third surface comprising a second slot guard and a fourth surface comprising the first surface of the feed material.

The exotic gas may be helium, hydrogen, neon, argon, pentafluoropropane or any mixture thereof.

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-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.

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.

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.

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

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

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

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

In 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;

releasing a feed material;

forming a localized exotic gas environment in between the imprint drum and the feed material to create a trapped exotic gas environment;

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.

The forming step may further comprise expelling an exotic gas in between the imprint drum and the feed material using a gas expulsion means.

The forming step may further comprise containing the expelled exotic gas in between the imprint drum and the feed material using a gas containment means.

The expulsion step may be performed at a gas flow rate in the range of 20 L per minute to 50 L per minute.

Brief Description Of Drawings

The accompanying drawings illustrate a disclosed embodiment and serves to explain the principles of the disclosed embodiment. It is to be understood, however, that the drawings are designed for purposes of illustration only, and not as a definition of the limits of the invention.

FIG. 1 is a schematic diagram illustrating a UV roll-to-roll nanoimprinting system.

FIG. 2 comprising FIG. 2A and FIG. 2B shows nanoimprint defects caused by trapped air, wherein Fig. 2A is an SEM image showing air trapping defects embedded in a UV roll-to-roll nanoprint field and FIG. 2B which is an optical microscopy image showing pull-out defects initiated by air trapping in a UV roll-to-roll nanoimprint field.

FIG. 3 comprising FIG. 3A and FIG. 3B shows a UV roll-to-roll imprinting apparatus, wherein FIG. 3A is a schematic diagram illustrating a UV roll-to-roll imprinting apparatus and FIG. 3B shows an image of an example implementation of the imprinting apparatus of FIG. 3A. The image is of the IMRE UV R2R system.

FIG. 4 comprising FIG. 4A to 4E shows the shaft mounting for the rewinding module, wherein FIG. 4A shows a schematic diagram illustrating a shaft mounting for the rewinding module according to an example embodiment, FIG. 4B shows an enlarged view of a portion of FIG. 4A, FIG. 4C shows an enlarged view of another portion of FIG. 4A, FIG. 4D shows an

alternate view of FIG. 4C and FIG. 4E shows and enlarged view of a portion of FIG. 4D.

FIG. 5 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.

FIG. 6 shows schematic diagrams illustrating sectional views of the guide rollers including the load cells mounted thereon respectively.

FIG. 7 comprising FIG. 7A and FIG. 7B shows the peeling means, wherein FIG. 7A shows a plan view illustrating the peeling means according to an example embodiment and FIG. 7B shows a perspective view of the peeling means of FIG. 7A.

FIG. 8 comprising FIG. 8A and FIG. 8B shows the imprint drum, wherein FIG. 8A shows a schematic diagram illustrating a sectional view of the imprint drum according to an example embodiment and FIG. 8B shows an image of an example implementation of the imprint drum of FIG. 8A.

FIG. 9A to FIG. 9D show schematic diagrams illustrating clamping a sheet mold according to an example embodiment.

FIG. 10A to FIG. 10D show schematic diagrams illustrating mounting the clamped sheet mold to a corresponding part according to an example embodiment.

FIG. 11 shows an image of an inkjet dispensing head according to an example implementation.

FIG. 12A to FIG. 12D 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.

FIG. 13A to FIG. 13E 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.

FIG. 14 shows a schematic diagram illustrating a press roller set according to an example embodiment.

FIG. 15 shows 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.

FIG. 16 comprising FIG. 16A and FIG. 16B shows a UV lamp assembly, wherein FIG. 16A shows a schematic diagram illustrating a UV lamp assembly suitable for curing the resin according to an example embodiment and FIG. 16B shows a perspective view of the UV lamp assembly of FIG. 16A.

FIG. 17 comprising FIG. 17A and FIG. 17B shows an imprinting apparatus according to an example embodiment, wherein FIG. 17A is a schematic diagram illustrating an imprinting apparatus according to an example embodiment incorporating a gaseous environment creation means to minimize air trapping and FIG. 17B is an image of an example implementation of the imprinting apparatus of FIG. 17A.

Fig. 18 comprising FIG. 18A, FIG. 18B and FIG. 18C shows the positioning of the gaseous environment creation means according to an example embodiment, wherein FIG. 18A is a schematic diagram illustrating the positioning of the gaseous environment creation means within a UV roll-to-roll imprinting system according to an example embodiment, FIG. 18B is an image of an example implementation of the gaseous environment creation means of FIG. 18A and FIG. 18C is an angled view of the gaseous environment creation means.

FIG. 19 is a schematic drawing of the air knife used in the imprinting apparatus comprising a gaseous environment creation means for the IMRE UV R2R system.

FIG. 20 shows a flow chart illustrating an imprinting method according to an example embodiment.

FIG. 21 comprising FIG. 21A to FIG. 21D shows representative optical microscopy images showing equivalent regions of the mold on two different samples (samples A and B) with and without application of an exotic gas (helium) using a gaseous environment creation means.

FIG. 22 shows images of UV roll-to-roll nanoimprinted, cured acrylate resin samples on polycarbonate web substrates, before 2201 and after 2202 applying the exotic gas (helium) air knife.

Definitions

The following words and terms used herein shall have the meaning indicated:

The term "air" for the purposes of this application, refers to ambient atmospheric air, that is the mixture of invisible odourless gases such as nitrogen, oxygen, carbon dioxide and argon that surrounds the earth and comprises the earth's atmosphere.

The term "positive pressure" for the purposes of this application, is any pressure applied to any pseudo-enclosure such that gas from outside the enclosure is limited from entering into the enclosure. The enclosure does not necessarily have to be air tight in order for the positive pressure to exist.

The word "substantially" does not exclude "completely" e.g. a composition which is "substantially free" from Y may be completely free from Y. Where necessary, the word "substantially" may be omitted from the definition of the invention.

Unless specified otherwise, the terms "comprising" and "comprise", and grammatical variants thereof, are intended to represent "open" or "inclusive" language such that they include recited elements but also permit inclusion of additional, unrecited elements.

As used herein, the terms "about" and "approximately", in the context of concentrations of components of the formulations, or where applicable, typically means +/- 5% of the stated value, more typically +/- 4% of the stated value, more typically +/- 3% of the stated value, more typically, +/- 2% of the stated value, even more typically +/- 1% of the stated value, and even more typically +/- 0.5% of the stated value.

Throughout this disclosure, certain embodiments may be disclosed in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the disclosed ranges. Accordingly, the description of a range should be considered to have specifically disclosed all the possible sub-ranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed sub-ranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

Disclosure of Optional Embodiments

FIG. 3A shows a schematic diagram illustrating an imprinting apparatus 300. FIG. 3B shows an image of an example implementation of the imprinting apparatus 300 of FIG. 3A. The imprinting apparatus 300 includes releasing means, in the form of an unwinding module 302, for releasing, e.g. rotatably, a feed material 301 (hereinafter interchangeably referred to as plastic web 301); an imprint drum 304 for forming a plurality of structures (not shown) adjacent to a first surface 303 of the feed material 301; and collecting means, in the form of a rewinding module 306, for collecting, e.g. rotatably, the feed material 301 together with the formed structures. The imprint drum 304 includes a rotatable inner member 802, and an outer member 804 releasably mounted to the inner member 802, as will be described in detail below with respect to FIG. 8A. Moreover, the outer member 804 has an engagement surface 834 (FIG. 8A and 8B) capable of accommodating at least one sheet mold 902 (FIG. 9). During operation, the at least one sheet mold 902 engages with the first surface 303 of the feed material 301 for forming the respective structures.

Smooth movement of the feed material or web 301 with a constant speed may be determined by the rotational speed (e.g. measured in rounds per minute (RPM)) of the imprint drum 304. The unwinding and rewinding modules 302, 306 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 301 may be

loaded to a shaft of the unwinding module 302 which may be equipped with a quick release core clamp, as will be discussed below with respect to FIG. 4A to 4E. The plastic web 301 is then guided by various rollers 308a-308e, 320a-b, including the imprint drum 304, before finally reaching the rewinding module 306. The rewinding module 306 may also have a shaft with a quick release core clamp of exactly the same design as the unwinding module 302. The core clamping, unwinding and rewinding, etc. of the feed material 301 may be controlled by software-automated mechanisms.

For example, sensing means, in the form of load cells 610a, 610b (FIG. 6), are employed in the rollers 320a, 320b respectively to measure web tension "on the fly". With reference to FIG. 6, the load acting on the surface of the respective roller 320a, 320b can be totalled, since the angle of the web 301 around the respective roller shell 602a, 602b 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 FIG. 3A and 3B, the imprinting apparatus 300 may further include a peeling module 310 for removing protective materials from the plastic feed. For example, the peeling module 310 includes a first winder 312 and first set of weight rollers 314 for removing a protective layer from the first surface 303, and a second winder 316 and a second set of weight rollers 318 for removing a protective layer from a second surface 305 of the plastic web 301. In addition, the imprinting system 300 may include cleaning means 322 for cleaning the plastic web 301 before imprinting, and a press roller set 224 to assist in pressing the plastic web 301 against the imprint drum 304. In the embodiment shown

in FIG. 3A and 3B, the imprinting apparatus 300 is a UV roll-to-roll imprinting apparatus. Dispensing means, in the form of a print head 326, is used to dispense a UV curable material on the sheet mold 902 (FIG. 9) from which the structures may be formed. In addition, a UV light source, in the form of UV lamps 328a, 328b, 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.

FIG. 4A shows a schematic diagram illustrating a shaft mounting mechanism 400 for the rewinding module 306 with a quick release core clamp. The roll of the plastic web 301 may be clamped by an inner surface of its hollow core tube.

With reference to FIG. 4A, clamping is essentially achieved by the sliding of two slanted faces. For example, an expansion blade 402 may slide on an expansion rod 404 where both components have slanted faces in contact. The expansion blade 402 may be secured axially but allowed to move in a radially outward direction. The expansion rod 404 may be guided and can only move in an axial direction. Air may be supplied from an air bearing rotary joint 406, which goes through a hole drilled to the centre of the shaft 408 to actuate a piston 410. The piston 410 pushes the expansion rod 404 and the expansion blade 402 contracts. When a new reel is inserted onto the shaft 408, the air supply is cut off and the spring 412 pushes back the expansion rod 404 and expands the expansion blade 402 to clamp the hollow core. The shaft 408 is coupled to an actuating means, in the form of a servo motor 401, via coupling 403. In addition, angular contact bearing 405 and ball bearing 407 facilitate rotational movement by the shaft 408 relative to the air bearing rotary

joint 406. Metal bushing 416a, 416b are placed between the shaft 408 and the expansion rod 404.

FIG. 4B shows an enlarged view of a portion of FIG. 4A illustrating the piston 410 and the spring 412, together with a floating air inlet 414, a metal bushing 416a and a wear ring 418.

FIG. 4C shows an enlarged view of a portion of FIG. 4A illustrating a rod expansion mechanism utilizing compressed air according to an example embodiment.

FIG. 4D shows an alternate view of FIG. 4C.

FIG. 4E shows and enlarged view of an air bearing portion 440 of FIG. 4D. 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) 406 utilizes compressed air, where the compressed air is fed in via the main shaft 408 while the shaft 408 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.

As shown in FIG. 4C to 4D, the ABRJ 406 includes 3 compressed air inlets 420, 422, 424. The middle inlet 420 may be used to supply compressed air to actuators, e.g. piston 410, while the other two inlets 422, 424 are used to supply compressed air to the air bearing 426. A groove, e.g. 423, is formed in the ABRJ 406 for each of the respective inlets 420, 422 424. There are four O-ring seals 428a-d between the interface of air bearing 426 and the housing 430 in one implementation. The O-rings 428a-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 432 at the interface between the air bearing 426 and the housing 430, as shown more clearly in FIG. 4D. The gap 432, which is about 0.2-0.3 mm, may cater for concentric tolerance of the air bearing 426. Since the O-rings 428a-d are elastic, a minor concentric inaccuracy can be tolerated. A locating pin 434 may be disposed in the housing 430 to set the air bearing 426 in the housing 430, to prevent axial and rotary movement.

With reference to FIG. 4E, compressed air enters at the midpoint of the air gap 436, a gap of about 4 - 6 microns (μm), forming a pressurized air film that separates the rotating shaft 408 and the inner wall of an air bearing 437. Typically, the rotary air bearing 437 in the example embodiments can sustain a force equal to the rectangular area of the diameter of the shaft 408 and the length of the air gap 436 multiplied by the air pressure. Compressed air that enters the air gap 436 may eventually reach air escape passages, e.g. 438, at both ends of the air gap 436.

FIG. 5 shows a schematic diagram illustrating a clamping mechanism 500 for the winder 312 or 316 (FIG. 3A) for collecting the materials from the plastic web 301 (FIG. 3) according to an example embodiment. A separate mechanism from that shown in FIG. 4A-4E is used in the clamping of the hollow core of the roll of the protective material. As shown in FIG. 5, the mechanism 500 uses an external pneumatic cylinder 502 to push and contract the expansion blade 504 via a spring 503 and a pull rod 510. A metal bushing 512 is placed between the pull rod 510 and a shaft 508. The rotation of the shaft 508 is facilitated by a set of angular contact bearing 505 and ball bearing 507. The basic working principles of the mechanisms 400 (FIG. 4A) and 500 are the

same; the main difference is that the rewinding (or unwinding) module 302, 306 (FIG. 3A) may allow direct coupling to the motor while the winder 312, 316 may require a timing pulley 506.

FIG. 6 show schematic diagrams illustrating sectional views of the guide rollers 320a, 320b (FIG. 3A) including the load cells 610a, 610b mounted thereon respectively. The guide rollers 320a, 320b includes respective rotatable roller shells 602a, 602b that are in contact with the plastic web. Each of the guide rollers 320a, 320b is clamped using a respective self-centering expansion clamp 604a, 604b. Further, each of the load cells 610a, 610b may be coupled to the respective guide roller 320a, 320b using fastening means inserted in a respective threaded hole 606a, 606b.

FIG. 7A shows a plan view illustrating the peeling means 310 (FIG. 3) according to an example embodiment. FIG. 7B shows a perspective view of the peeling means 310 of FIG. 7A. It will be appreciated that the plastic web 301 (FIG. 3) generally comes with protective plastic cover layers 702a, 702b 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 304, these protective layers 702a, 702b are removed. The peeling means 310 utilizes two identical sub-systems 710a, 710b each including a winder 312, 316 and a weight roller 314, 318 (FIG. 3A), to wind, tension and collect a respective protective layer 702a, 702b from each side of the web 301. The weight rollers 314, 318 shown in FIG. 7A and 7B may be idler rollers mounted on a linear bearing guidance system 706 in one implementation. Each weight roller 314, 318 can move up and down freely within a certain span 704a, 704b. The

protective layers 702a, 702b wrap around the respective weight rollers 314, 318 such that, when the winders 312, 316 rotate, the slack from the respective protective layers 702a, 702b may be tensioned by the weight of the weight rollers 314, 318. The sub-systems 710a, 710b may operate independently of each other. When the weight roller 314, 318 reaches the lower end of the span 704a, 704b, a first sensor activates the motor of the winder 312, 316 to wind the respective protective layer 702a, 702b onto the respective core. During winding, the weight roller 314, 318 may move upwards until it reaches the upper end of the span 704a, 704b and triggers a second sensor to stop the motor of the winder 312, 316. The weight of the weight rollers 314, 318 can be adjusted by varying the pressure of an air cylinder counter-balancing the weight of the roller. The shafts of the winders 312, 316 are also equipped with quick-release core clamps.

FIG. 8A shows a schematic diagram illustrating a sectional view of the imprint drum 304 (FIG. 3) according to an example embodiment. FIG. 8B shows an image of an example implementation of the imprint drum 304 of FIG. 8A. As described above, the imprint drum 304 has a rotatable inner member 802 and an outer member 804 releasably mounted to the inner member 802. With reference to FIG. 8A, the imprint drum 304 also includes a main support shaft 806 where the inner member 802 rotates on. The outer member 804 may be secured to the inner member 802 by a tapered face 808 on one side and another split taper ring 810 on the opposing side. This setup may enable easy removal of the outer member 804, e.g. when the outer member 804 is replaced by one of a different size. In other words, the size of the imprint drum 804 may be quickly adjusted by replacing an existing outer member 804

and mounting a suitably-sized outer member 804. The imprint drum 304 may rotate on bearings 812, 814 preloaded with a spring 816 to eliminate the axial play of the bearings 812, 814. One end 824 of the driving shaft 806 may be coupled, e.g. using coupling 818, to a servo motor 820 with a gear reducer 822, and the other end 826 may be coupled to the outer member 804. Typically, the imprint drum 304 is configured to rotate at a constant speed. The imprint drum 304 may also include a main support 828 and a bearing spacer 830 as shown in FIG. 8A. In some embodiments, dispensing means, e.g. in the form of the print head 326 (FIG. 3A and FIG. 3B) may be mounted adjacent the imprint drum 304.

As illustrated more clearly in FIG. 8B, in some embodiments, the outer member 804 may have at least one slot 832, typically multiple slots 832a-b, where a respective sheet mold 902 (FIG. 9) can be mounted (e.g. a nickel electroformed sheet mold). Each slot 832a-b can receive a corresponding stainless steel part 1002 (FIG. 10) that is configured to precisely fit into the slot 832a-b in order to create a continuous, smooth drum engagement surface 834. In a preferred embodiment, a plurality of sheet molds 902, each having respective feature resolution, design, etc., can thus be attached to the engagement surface 834.

The aforementioned parts are also configured for mounting the respective sheet mold 902 under tension, such that the sheet mold 902 can be mounted on the imprint drum 304 as if it were wrapped on the drum 304 while only occupying a portion of the drum engagement surface 834 (as opposed to being wrapped around the entire drum engagement surface 834). Typically, the sheet mold 902 is mounted onto the corresponding mounting part 1002, which is then mounted to a

respective slot 832a-b, as will be described in detail below with respect to FIG. 9Aa to 9D and 10A to 10D. 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 304. However, it would be appreciated that in alternate embodiments, the slots 832a-b can be removed and replaced with another outer member 804 for the purposes of mounting a large sheet mold 902 around the entire imprint drum 304. 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.

FIG. 9A to 9D and 10A to 10D show schematic diagrams illustrating mounting a sheet mold 902 to a corresponding part 1002 according to an example embodiment. Typically, the sheet mold 902 (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 902 may be made from a different material, including but not limited to NiCo (nickel, cobalt alloy), or fluoropolymers (ETFE, PTFE, Teflon), or silicones, or ordinary plastics such as polycarbonate, PMMA, PET, etc. In further embodiments, the sheet mold 902 may be a hybrid mold containing a hard textured surface composed of, for example a silicon dioxide, quartz, metal, hard polymer, hard silicone (h-PDMS for example), fluoropolymer or other hard coating or layer on top of a conformal backing layer formed from a softer 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 1002 are reinforced

with clamps 904. As shown in FIG. 9A to 9D, each end of the nickel sheet mold 902 is gripped and sandwiched by a separate metal bar 906, forming a clamp on each side that is secured by screws 908. For a permanent mount, epoxy glue can also be applied between the metal bars 906 and the nickel mold 902, providing an even load distribution when tensioning.

As shown in FIG. 10A to 10D, the reinforced nickel mold 902 is then secured and tensioned onto the corresponding part 1002 (also referred to as a backing plate) with an arc parameter exactly equal to that of the imprint drum 304 (FIG. 3A). Two filler bars 1004a, 1004b (FIG. 10C to 10D) may also secured on both sides of the part 1002 after the latter is slot mounted on the outer member 804 (FIG. 8A) of imprint drum 304. These filler bars 1004a, 1004b may help to cover and restore the part 1002 to full arc, to provide a continuous engagement surface 834 (FIG. 8A).

In alternate embodiments, the sheet mold 902 (FIG. 9A) may be mounted to the imprint drum 304 (FIG. 8A) by mechanically fastening the sheet mold 902 directly to engagement surface 834 (FIG. 7A to 7D) the imprint drum 304, without carving slots 832a-b (FIG. 8B) in outer member 804. For example, the respective mold or molds 902 may be directly fastened, e.g. using screws, to the outer member 804 with filler bars, instead of mounting the mold 902 to a stainless steel part 1002 (FIG. 10A) that is then slotted into the drum 204.

In further alternate embodiments, the sheet mold 902 may be mounted by gluing or magnetically attaching the mold 902 to the engagement surface 934 (FIG. 9A and 9B) of the imprint drum 304, where the area of the mold 902 is small enough such that multiple molds may be (but not necessarily) mounted on

the imprint drum 204 in this manner. For example, for magnetic attachment, the imprint drum 304 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 304 having an inner member 802 and an outer member 804 may still be used. In cases where multiple molds 902, each having its own resolution and design, are used on one imprint drum 304, the mold mounting as described above can be carried out for each of the molds. The outer member 804 can be removed and replaced with a different outer member containing different mounted parts 902, different mounted molds 902, or molds 902 mounted using a different mounting method.

FIG. 11 shows an image of an inkjet dispense head 1100 (i.e. print head 326 shown in FIG. 3A) according to an example implementation. In embodiments using UV curing, a UV curable resin is dispensed from the inkjet dispense head 1100 directly onto the mounted nickel sheet mold 902 (FIG. 9A). This may be an advantageous arrangement compared to the commonly accepted approach of dispensing on the web 301 (FIG. 3). This is because the dispensed droplets on the web 301 need to be precisely aligned and timed to join with the mold 902 at exactly the right moment when the web 301 and mold 902 are pressed together by the pressure rollers 1402a-b (FIG. 14). It may be much easier to fix the dispense head 1100 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 1100 to time the dispensing with the arrival of the mold 902 (or for continuous mold, simply dispense continuously).

FIG. 12A to 12D show schematic diagrams illustrating a UV roll-to-roll nanoimprinting process utilizing a continuous flow of a UV curable resin 1202 according to an example embodiment. As shown in FIG. 12A, in Step 1, the resin 1202, which is contained in a container 1204 of the dispense head 1100 (FIG. 11) is deposited on a mold 1206 mounted on an imprint drum 1208 and having a plurality of mold cavities 1210 and mold protrusions 1212. As shown in FIG. 12b, in Step 2, a web 1214 is brought into contact with the deposited resin for pressing against the resin. As shown in FIG. 12C, in Step 3, after the resin is spread against the web 1214, e.g. by pressure rollers 1402a-b (FIG. 14), the resin is polymerized by UV radiation generated by a UV light source. As shown in FIG. 12d, in Step 4, the solidified structures 1218 adjacent to (e.g. attached to) the surface of the web 1214 are removed from the mold 1206. [Normally it is not possible to remove resin in an automated fashion once it is deposited on the mould/web].

In an example implementation, liquid dispensing of the UV curable resin 1202 may be achieved by a continuous dispensing of resin droplets on the mold 1206 using a print head 1100 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 1202 appears as 128 lines of droplets deposited on the sheet mold 1206 while the latter travels beneath the print head 1100. The volume of a single droplet may be only about 10 picoliters (pl) (i.e. a sphere

of diameter 13.37 micron).[This should be a range from 10 - 100 picoliters]. In order to control the shape of the dispensed area on the mold 1206, 1-bit (black and white) images may be loaded into the dispensing software prior to actual dispensing. These 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 1100 may be fired, and vice-versa for white regions.

FIG. 13A to 13E show schematic diagrams illustrating a UV roll-to-roll nanoimprinting process utilizing a drop-on demand deposition of a UV curable resin 1302 according to an alternate embodiment. As shown in FIG. 13A, in Step 1, the resin 1302, which is contained in a container 13204 of the dispense head 1100 (FIG. 11) is deposited on a mold 1306 mounted on an imprint drum 1308 and having a plurality of mold cavities 1310 and mold protrusions 1312. As illustrated more clearly in FIG. 13B, individual drops of the resin 1302 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 FIG. 13b, in Step 2, a web 1314 is brought into contact with the deposited drops for pressing against the drops. As shown in FIG. 13C, in Step 3, after the resin is spread against the web 1314, e.g. by pressure rollers 1402a-b (FIG. 14), the resin is polymerized by UV radiation generated by a UV light source. As shown in FIG. 13D, in Step 4, the solidified structures 1318 attached to the surface of the web 1314 are removed from the mold 1206. In this embodiment, there is

typically little excess 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 300 (FIG. 3A). This system may allow fine adjustment of local dispensed volume to place more resin 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.

FIG. 14 shows a schematic diagram illustrating a press roller set 324 (FIG. 3A) according to an example embodiment. As described above, after deposition, the mold 1206, 1306 (FIG. 12A, 13A) with deposited resin is then pressed against the plastic web 301 (FIG. 3A) (which is fed in by the web unwinding module 302 (FIG. 3)) by the pressure roller set 324. For example, the press roller set 324 includes two polyurethane rollers 1402a, 1402b with shore hardness of about 60~80. Each roller 1402a, 1402b may be actuated by a respective low friction pneumatic cylinder 1404a, 1404b,

where the pressure of each cylinder 1404a, 1404b can be varied to adjust to the web tension tracking. The principal function of these rollers 1402a, 1402b 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.

FIG. 15 shows a schematic diagram illustrating the results of the pressing action by the imprint drum 1502 and press rollers 1504a, 1504b on the plastic web 1506 according to an example embodiment. Here, the sheet mold 1507 is mounted on a respective mold slot 1508. After the mold 1507 engages with the web 1506, structures 1510, 1512 are formed and disposed on a surface 1514 of the web 1506 based on the respective mold 1507.

The next step in the example embodiment using UV curable resin is to polymerize and solidify the resin. FIG. 16A shows a schematic diagram illustrating a UV lamp 1600 assembly suitable for curing the resin according to an example embodiment. FIG. 16B shows a perspective view of the UV lamp assembly 1600 of FIG. 16A. In some implementations, two Mercury UV lamp assemblies 1600 (i.e. UV light sources 328a, 328b (FIG. 3A)) are installed under the imprint drum 304 (FIG. 3A) to cure the resin. Each UV lamp assembly 1600 includes a UV lamp 1602 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 1602 may be installed at the foci of a parabolic reflector 1604. Since the UV lamp 1602 may generate a lot of heat, a "cold mirror" 1606 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 1606 and

is dumped to a heat sink 1608. The cold mirror 1606 may be positioned at 45° with respect to the irradiation from the lamp 1602, which is directionally concentrated by the back-end parabolic reflector 1604. As illustrated in FIG. 16B, the lamp 1602 may be disposed in housing 1610 which is insulated with a heat-resistant material. Air is sucked into the housing 1510 via openings 1612, 1614 in the housing wall to cool the lamp 1602 as well as the heat sink 1608. In addition, since the UV lamp 1602 cannot be turned on or off instantly, the lamp 1602 normally remains turned on during operation, and a shutter 1616 is installed so that it can block the UV rays when necessary. For example, the shutter 1616 may be controlled by a rotary actuator 1618 for opening or closing a UV radiation window 1620, as shown in FIG. 16B.

With reference to FIG. 3A, once the resin is fully cured by the UV light source 328a, 328b (UV lamp assembly 1600), the imprint drum 304 is rotated until separation with the web 301 takes place. Following that, the imprinted web together with the formed structures is re-wound by the web rewinding module 306. 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).

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, silicones, 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.

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 with a featureless shell for wrapping a large sheet mold around the imprint drum itself, or for mounting a seamless mold shell.

Forming a localized exotic gas environment during a UV roll-to-roll nanoimprinting process may be difficult as there are moving parts, specifically the feed material itself, that requires minimal contact with other surfaces. However, in accordance with the present disclosure, by precisely injecting an exotic gas immediately at the point where the resin, the feed material and the mold are joined together and by creating a pseudo-enclosure at the point of injection, a gas environment that is more soluble in the resin than ambient atmosphere, is advantageously formed. This may facilitate gas dissolution and elimination of oxygen

inhibition while circumventing the time and costs that may be consumed in forming a global exotic gas environment for the entire apparatus chassis, thereby advantageously reducing the amount of defects observed in the nanoimprinting products.

FIG. 17A is a schematic diagram illustrating an imprinting apparatus 1700 according to an example embodiment incorporating a gaseous environment creation means 1702 to form a localized exotic gas environment. The apparatus 1700 may be essentially identical to the UV roll-to-roll imprinting apparatus 300 described in FIG 3 to FIG. 16, incorporating an additional component which is the gaseous environment creation means 1702. The first surface 303 (FIG. 3) of the feed material 301 (FIG. 3) may be in contact with the outer surface of the imprint drum 304 (FIG. 3). The imprint drum 304 may further comprise a sheet mold 902 (FIG. 9) on the outer surface of the imprint drum 304. The gaseous environment creation means 1702 may be configured in between the first surface 303 of the feed material 301 and the imprint drum 304 or the sheet mold 902 (FIG. 9) attached the outer surface of the imprint drum 304, at the point of contact between the feed material 301, the imprint drum 304 or the sheet mold 902 (FIG. 9) attached to the outer surface of the imprint drum 304, and the press roller set 324 (FIG. 3). The gaseous environment creation means 1702 advantageously creates a localized exotic gas environment in between the imprint drum 304 or the sheet mold 902 (FIG. 9) attached the outer surface of the imprint drum 304 and the first surface 303 of the feed material 301. FIG. 17B is an image of an example implementation of the imprinting system of FIG. 17A.

FIG. 18A is a schematic diagram illustrating the positioning of the gaseous environment creation means 1702 (FIG. 17) within a UV roll-to-roll imprinting system 1700 (FIG. 17) according to an example embodiment. The gaseous environment creation means 1702 (FIG. 17) comprises a gas expulsion means 1800 and a gas containment means 1802. The gas expulsion means is advantageously configured to expel an exotic gas into the nip 1804 created by the first surface 303 of the feed material 301 and the imprint drum 304 or the sheet mold 902 (FIG. 9) attached to the outer surface of the imprint drum 304. The gas containment means 1802 is provided to contain the expelled gas in a pseudo-enclosed zone 1806. The pseudo-enclosed zone 1806 may not be completely enclosed.

FIG. 18B is an image of an example implementation of the gaseous creation means of FIG. 18A. FIG. 18B shows that the gas expulsion means 1800 further comprises a gas feed means 1806 and an air knife 1808. The gas feed means 1806 is connected to the air knife 1808. The connecting may be done via a tube. The gas feed means 1806 may feed the exotic gas into the air knife 1808.

The air knife may be any apparatus that comprises a pressurized gas plenum containing a series of holes or continuous slots through which pressurized gas may exit in a laminar flow pattern. The exit gas velocity may then create an impact gas velocity onto the surface of the object to which the air is directed. The air knife 1808 expels the exotic gas fed from the gas expulsion means into the nip of the imprinting system 1700. The air knife 1808 is positioned in close proximity to the feed material 301 above and the imprint drum 304 or the sheet mold 902 (FIG. 9) attached to the outer surface of the imprint drum 304 below. The air knife 1808 may

be positioned at a distance in the range of 0.01 mm to 1.5 mm from the feed material 301 above and at a distance in the range of 0.01 mm to 1.5 mm from the imprint drum 304 or the sheet mold 902 (FIG. 9) attached to the outer surface of the imprint drum 304 below.

FIG. 18C is an angled view of the gaseous environment creation means 1702 (FIG. 17) showing how a pseudo-enclosed zone 1806 is formed at the nip 1804 using the gas containment means 1802. The gas containment means 1802 further comprises a first surface comprising the outer surface of the air knife 1808, a second surface comprising a first slot guard 1810a, a third surface comprising a second slot guard 1810b and a fourth surface comprising the first surface 303 of the feed material 301. The triangular opening on either end of the space created by the air knife 1808, feed material 301 and imprint drum 304 or the sheet mold 902 (FIG. 9) attached to the outer surface of the imprint drum 304, is enclosed with additional slot guards 1810a and 1810b.

The combination of positioning of the gas expulsion means 1800 and the pseudo-enclosure created by the gas containment means 1802 advantageously allows the formation of a pseudo-enclosed zone 1806. Although the pseudo-enclosed zone 1806 may not be completely enclosed, when sufficient pressure is applied by the exotic gas being expelled by the gas expulsion means 1800, the pseudo-enclosed zone 1806 acquires a positive pressure. This positive pressure applied to the gas containment means 1802 arising from the high flow rate of the exotic gas expelled by the gas expulsion means 1800, prevents air from ambient atmosphere to enter into the pseudo-enclosed zone 1806. As such, a relatively pure exotic gas environment is formed at the nip 1804, allowing the contact between the

feed material 301 and imprint drum 304 or the sheet mold 902 (FIG. 9) attached to the outer surface of the imprint drum 304, to occur in a localized exotic gas environment.

The localized exotic gas environment is simultaneously a trapped localized exotic gas environment. Air refers to ambient atmospheric air, that is the mixture of invisible odourless gases such as nitrogen, oxygen, carbon dioxide and argon that surrounds the earth and comprises the earth's atmosphere. In the trapped localized exotic gas environment, the concentration of ambient "air" is greatly reduced because of the injection of exotic gas into the pseudo-enclosure. The trapped localized exotic gas environment is substantially comprised of exotic gas. In the trapped localized exotic gas environment, the exotic gas has improved solubility in the resin, and the increased solubility becomes the dominant behaviour of the gas molecules in the environment. The trapped localized exotic gas environment is a gaseous environment wherein the gas in the gaseous environment is more soluble in the resin deposited on the feed material 301 compared to gas in ambient atmosphere. By excluding air during the contact of the feed material 301 and the imprint drum 304 or the sheet mold 902 (FIG. 9) attached to the outer surface of the imprint drum 304, bubble formation and oxygen inhibition may be at least partially minimized, facilitating a reduction in nanoimprinting defects in the nanoimprinting product. By creating an exotic gas environment as the feed material 301 contacts the imprint drum 304 or the sheet mold 902 (FIG. 9), the trapped exotic gas environment which is a gaseous environment wherein the gas in the gaseous environment is more soluble in the resin deposited on the feed material 201 compared to gas in ambient atmosphere, may

at least partially minimize bubble formation through dissolution of trapped bubbles as well as minimize oxygen inhibition, facilitating a reduction in defects in the nanoimprinting product.

The exotic gas used in the nanoimprinting system 1700 may be a gas comprising a low atomic weight element or a hydrofluorocarbon. The exotic gas may dissolve in the feed material 301 to at least partially minimize bubble formation and oxygen inhibition. The exotic gas may be selected from the group consisting of any one of helium, hydrogen, neon, argon, pentafluoropropane and any mixture thereof. The exotic gas may be helium or pentafluoropropane.

The gaseous environment creation means 1702 is used to form a trapped exotic gas environment in the pseudo-enclosed zone 1806. The trapped exotic gas environment is a gaseous environment wherein the gas in the gaseous environment is more soluble in the resin deposited on the feed material 301 compared to gas in ambient atmosphere. The forming step further comprises expelling an exotic gas in between the imprint drum 304 or the sheet mold 902 (FIG. 9) attached to the outer surface of the imprint drum 304 and the feed material 301 using a gas expulsion means 1800. The forming step further comprises containing the expelled exotic gas in between the imprint drum 304 or the sheet mold 902 (FIG. 9) and the feed material 301 using a gas containment means 1802.

The gas expulsion step may be performed at a gas flow rate in the range of about 20 L per minute to about 50 L per minute.

FIG. 19 is a schematic drawing of the air knife 1808 (FIG. 18) and the slot guards 1810 (comprising 1810a and 1810b) used in the imprinting system 1700 for the IMRE UV R2R system.

The air knife 1808 (FIG. 18) and slot guards 1810 described in FIG. 19 is a representative air knife that can be purchased from SOLVES.

FIG. 20 shows a flow chart 2000 illustrating an imprinting method according to an example embodiment. At step 2002, 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 may be provided. At step 2004, a feed material may be released. At step 2006, a localized exotic gas environment may be formed in between the imprint drum and the feed material. At step 2008, at least one sheet mold may be engaged with a first surface of the feed material for forming a plurality of respective structures adjacent to said first surface. At step 2010, the feed material together with the formed structures may be 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 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 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.

Examples

Non-limiting examples of the invention will be further described in greater detail by reference to specific Examples, which should not be construed as in any way limiting the scope of the invention.

FIG. 21 comprising FIG. 21A to FIG. 21D shows representative optical microscopy images showing equivalent regions of the mold on two different samples (samples A and B) with and without application of an exotic gas (helium) using a gaseous environment creation means in a UV roll-to-roll nanoimprint system. Sample A has a 5 μm line and space region while sample B has a 30 μm line and space region. Samples were otherwise produced under the same processing conditions. The following parameters were used for the printing: 10 meters/min, 1 second 395nm UVLED exposure, YNIL-R2-1 resin (Young Chang Chemical), 400kPa roller pressure.

FIG.21A shows sample A without application of helium and FIG. 21B shows sample A with the application of helium at the nip. FIG. 21C shows sample B without application of helium and FIG. 21D shows sample B with the application of helium at the nip. FIG. 21A and FIG. 21C clearly show that samples A and B without the application of helium have trapped air defects in the printed product, as the printed lines in these samples are not continuous, not defined, not clear or portions of the printed lines and/or the imprinted coating are missing. In contrast, FIG. 21B and FIG. 21D showing

samples A and B with the application of helium at the nip show printed lines that are significantly more continuous, defined and clear. This example shows that the application of a localized exotic gas environment using a gas environment creation means can improve the quality of nanoimprints, even for roll-to-roll nanoimprinting systems that comprise moving parts. The use of helium improves the quality of imprinted fields through dissolution of trapped air and prevention of oxygen inhibition, allowing for a more complete cure, and better adhesion to the substrate]

FIG. 22 shows images of UV roll-to-roll nanoimprinted, cured acrylate resin samples on polycarbonate web substrates, before 2201 and after 2202 applying the exotic gas (helium) air knife. When helium is used, for example, to modify the atmosphere at the nip where the resin is deposited, any trapped air passing beneath the pressure rollers will have a high concentration of helium which is significantly more soluble in UV curable resins than air (particularly nitrogen). The high concentration of helium increases the likelihood of trapped air defects 2210 dissolving into the resin. Further, the replacement of oxygen in the atmosphere with helium results in less oxygen inhibition of the polymerization reaction for acrylate resins, resulting in fewer edge defects 2212, as the oxygen generally affects the edges of the sample that interface with the ambient.

Applications

The apparatus and method would have applications in any UV roll-to-roll nanoimprinted product that would benefit from drastic reduction in defect density and significant improvement

in mechanical properties (incl. mechanical integrity) due to an improved curing state.

For example, 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 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, flexible electronics and many others.

In addition, as the delivery of a helium or exotic gas environment is generally useful for improving the technology of UV nanoimprinting, the disclosed apparatus and method may lead to research, development and manufacture of new roll-to-roll nanoimprinting tools.

It will be apparent that various other modifications and adaptations of the invention will be apparent to the person skilled in the art after reading the foregoing disclosure without departing from the spirit and scope of the invention and it is intended that all such modifications and adaptations come within the scope of the appended claims.

Claims

1. An imprinting apparatus comprising:

releasing means for releasing a feed material;

an imprint drum configured to engage with a first surface of the feed material for forming a plurality of structures adjacent to said first surface;

gaseous environment creation means for forming a localized exotic gas environment in between the imprint drum and the first surface of the feed material; and

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

2. The apparatus as claimed in claim 1, wherein the imprint drum comprises a rotatable inner member, and an outer member releasably mounted to the inner member.

3. The apparatus as claimed in claim 2, 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.

4. The apparatus as claimed in any one of the preceding claims, wherein the engagement surface has at least one slot for receiving at least one detachable part having the respective sheet mold mounted thereon.

5. The apparatus as claimed in any one of the preceding claims, 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.

6. The apparatus as claimed in any one of the preceding claims, wherein the releasing means and collecting means each comprise a roller mounted on a respective air bearing rotary joint.

7. 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.

8. The apparatus as claimed in claim 7, wherein the guiding means comprises:
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 adjusting respective speeds of the releasing and collecting means.

9. The apparatus as claimed in claim 8, further comprising peeling means for removing a protective layer from at least one of the first surface and the second surface of the feed material.

10. The apparatus as claimed in claim 8 or 9, 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.

11. The apparatus as claimed in any one of the preceding claims, wherein the gaseous environment creation means comprises a gas expulsion means and a gas containment means.

12. The apparatus as claimed in claim 11, wherein the gas expulsion means further comprises a gas feed means and an air knife.

13. The apparatus as claimed in claim 11 or 12, wherein the gas containment means further comprises a first surface comprising the outer surface of the air knife, a second surface comprising a first slot guard, a third surface comprising a second slot guard and a fourth surface comprising the first surface of the feed material.

14. The apparatus as claimed in any one of claims 11 to 13, wherein the exotic gas is helium, hydrogen, neon, argon, pentafluoropropane or any mixture thereof.

15. The apparatus as claimed in any one of the preceding claims, wherein the formed structures are detachably disposed on the first surface.

16. The apparatus as claimed in claim 15, 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.

17. The apparatus as claimed in claim 16, 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.

18. The apparatus as claimed in claim 16 or 17, further comprising controlling means for controlling a volume of the UV curable material at a predetermined position on the respective sheet mold.

19. The apparatus as claimed in any one of claims 16 to 18, further comprising at least one UV light source for curing the formed structures disposed on the first surface of the feed material.

20. The apparatus as claimed in any one of the preceding claims, wherein the formed structures are integral with the feed material.

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

22. 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, silicones and plastics.

23. The apparatus as claimed in any one of claims 1 to 21, wherein the at least one sheet mold comprises a hybrid mold having a hard coating layer on top of a conformal backing layer.

24. 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.

25. 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;

forming a localized exotic gas environment in between the imprint drum and the feed material to create a trapped exotic gas environment;

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.

26. The method as claimed in claim 25, wherein the trapped exotic gas environment is a gaseous environment wherein the gas in the gaseous environment is more soluble in resins deposited on the feed material compared to gas in ambient atmosphere.

27. The method as claimed in claim 25 or 26, wherein the forming step further comprises expelling an exotic gas in between the imprint drum and the feed material using a gas expulsion means.

28. The method as claimed in claim 25 to 27, wherein the forming step further comprises containing the expelled exotic gas in between the imprint drum and the feed material using a gas containment means.

29. The method as claimed in any one of claims 25 to 28, wherein the expulsion step is performed at a gas flow rate in the range of 20 L per minute to 50 L per minute.