MICROREPLICATED FILMS HAVING DIFFRACTIVE FEATURES ON MACRO-SCALE FEATURES

Background

Machining techniques can be used to create a wide variety of work pieces such as microreplication tools. Microreplication tools are commonly used for extrusion processes, injection molding processes, embossing processes, casting processes, or the like, to create microreplicated structures. The microreplicated structures may comprise optical films, abrasive films, adhesive films, mechanical fasteners having self-mating profiles, or any molded or extruded parts having microreplicated features of relatively small dimensions, such as dimensions less than approximately 1000 microns.

The microstructures can also be made by various other methods. For example, the structure of the master tool can be transferred on other media, such as to a belt or web of polymeric material, by a cast and cure process from the master tool to form a production tool; this production tool is then used to make the microreplicated structure. Other methods such as electroforming can be used to copy the master tool. Another alternate method to make a light directing film is to directly cut or machine a transparent material to form the appropriate structures. Other techniques include chemical etching, bead blasting, or other stochastic surface modification techniques.

Summary

An optical film, consistent with the present invention, includes a substrate and microreplicated features on a major surface of the substrate. The microreplicated features include macro-scale features and one or more diffractive features on the macro-scale features. The films can be made from work pieces machined with tool tips having diffractive features. The tool tip forms both the macro-scale features and diffractive features while machining the work piece. A coating process can then be used to make the optical films from the machined work piece.

Brief Description of the Drawings

The accompanying drawings are incorporated in and constitute a part of this specification and, together with the description, explain the advantages and principles of the invention. In the drawings,

FIG. 1 is a diagram of a cutting tool system for making microstructures in a work piece;

FIG. 2 is a diagram illustrating a coordinate system for a cutting tool;

FIG. 3 is a diagram of an exemplary PZT stack for use in a cutting tool;

FIG. 4A is a perspective view of a tool tip carrier;

FIG. 4B is a front view of a tool tip carrier for holding a tool tip;

FIG. 4C is a side view of a tool tip carrier;

FIG. 4D is a top view of a tool tip carrier;

FIG. 5A is a perspective view of a tool tip;

FIG. 5B is a front view of a tool tip;

FIG. 5C is a bottom view of a tool tip;

FIG. 5D is a side view of a tool tip;

FIG. 6A is a top sectional view of an FTS actuator;

FIG. 6B is a front sectional view illustrating placement of a PZT stack in an actuator;

FIG. 6C is a front view of an actuator;

FIG. 6D is a back view of an actuator;

FIG. 6E is a top view of an actuator;

FIGS. 6F and 6G are side views of an actuator;

FIG. 6H is a perspective view of an actuator;

FIG. 7A is a diagram illustrating an interrupted cut with substantially equal taper-in and taper-out angles into and out of a work piece;

FIG. 7B is a diagram illustrating an interrupted cut with a taper-in angle less than a taper-out angle into and out of a work piece;

FIG. 7C is a diagram illustrating an interrupted cut with a taper-in angle greater than a taper-out angle into and out of a work piece;

FIG. 8 is a diagram conceptually illustrating microstructures that can be made using the cutting tool system having an interrupted cut FTS actuator;

FIG. 9A is a perspective view of a machined tool tip;

FIG. 9B is a front view of a machined tool tip;

FIG. 9C is a bottom view of a machined tool tip;

FIG. 9D is a side view of a machined tool tip;

FIG. 10A is a side view of a multi-tip tool having machined and non-machined tool tips;

FIG. 10B is a side view of a multi-tip tool having multiple machined tool tips;

FIGS. 11A and 11B are side and perspective views, respectively, conceptually illustrating microstructures that can be made using the cutting tool system having an FTS actuator with at least one machined tool tip;

FIGS. 12A and 12B are side and perspective views, respectively, conceptually illustrating microstructures that can be made using the cutting tool system having an interrupted cut FTS actuator with at least one machined tool tip;

FIG. 13A is a side view of a tool tip with diffractive features on both facets;

FIG. 13B is a side view of another tool tip with diffractive features on both facets;

FIG. 14 is a side view of a tool tip with diffractive features on one facet;

FIG. 15A is a side view of a tool tip with diffractive features using step height variation;

FIG. 15B is a side view of another tool tip with diffractive features using step height variation;

FIG. 16 is a side view of a tool tip with diffractive features along 90° facet sides;

FIG. 17 is a side view of a tool tip with diffractive features along a flat tip;

FIG. 18 is a side view of a tool tip with diffractive features along a curved tip;

FIG. 19 is a side view of a tool tip with diffractive features formed in steps;

FIG. 20 is a side view of a tool tip with diffractive features having a lenticular shape;

FIG. 21 is a side view of a tool tip with diffractive features along curved facets;

FIG. 22 is a side view of a tool tip with diffractive features along multiple linear facets;

FIG. 23A is a side view of a tool tip before ion milling;

FIG. 23B is a side view of the tool tip of FIG. 23A after using ion milling to form diffractive features in the same plane on the tip;

FIG. 24A is a side view of a tool tip before ion milling;

FIG. 24B is a side view of the tool tip of FIG. 24A after using ion milling to form diffractive features in different planes on the tip;

FIG. 25A is a first perspective view of a non-FTS tool post;

FIG. 25B is a second perspective view of a non-FTS tool post;

FIG. 25C is a top view of a non-FTS tool post;

FIG. 26A is a perspective view of a shank for holding a tool tip on a non-FTS tool post;

FIG. 26B is a front view of a shank for holding a tool tip;

FIG. 26C is a bottom view of a shank for holding a tool tip;

FIG. 26D is a side view of a shank for holding a tool tip;

FIG. 27A is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 13A;

FIG. 27B is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 13B;

FIG. 28 is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 14;

FIG. 29A is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 15A;

FIG. 29B is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 15B;

FIG. 30 is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 16;

FIG. 31 is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 17;

FIG. 32 is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 18;

FIG. 33 is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 19;

FIG. 34 is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 20;

FIG. 35 is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 21; and

FIG. 36 is a perspective view illustrating a representative portion of a film made from a work piece machined with a tool tip corresponding with the tool tip shown in FIG. 22.

Detailed Description

Cutting Tool System

General diamond turning techniques are described in PCT Published Application WO 00/48037, incorporated herein by reference as if fully set forth. The apparatus used in methods and for making optical films or other films can include a fast servo tool. As disclosed in WO 00/48037, a fast tool servo (FTS) is a solid state piezoelectric (PZT) device, referred to as a PZT stack, which rapidly adjusts the position of a cutting tool attached to the PZT stack. The FTS allows for highly precise and high speed movement of the cutting tool in directions within a coordinate system as further described below.

FIG. 1 is a diagram of a cutting tool system 10 for making microstructures in a work piece. Microstructures can include any type, shape, and dimension of structures on, within, or protruding from the surface of an article. For example, microstructures created using the actuators and system described in the present specification can have a 1000 micron pitch, 100 micron pitch, 1 micron pitch, or even a sub-optical wavelength pitch around 200 nanometers (nm). Alternatively, in other embodiments, the pitch for the microstructures can be greater than 1000 microns, regardless as to how they are cut.

These dimensions are provided for illustrative purposes only, and microstructures made using the actuators and system described in the present specification can have any dimension within the range capable of being tooled using the system.

System 10 is controlled by a computer 12. Computer 12 has, for example, the following components: a memory 14 storing one or more applications 16; a secondary storage 18 providing for non-volatile storage of information; an input device 20 for receiving information or commands; a processor 22 for executing applications stored in memory 14 or secondary storage 18, or received from another source; a display device 24 for outputting a visual display of information; and an output device 26 for outputting information in other forms such as speakers for audio information or a printer for a hardcopy of information.

The cutting of a work piece 54 is performed by a tool tip 44. An actuator 38 controls movement of tool tip 44 as work piece 54 is rotated by a drive unit and encoder 56, such as an electric motor controlled by computer 12. In this example, work piece 54 is shown in roll form; however, it can be implemented in planar form. Any machineable materials could be used; for example, the work piece can be implemented with aluminum, nickel, copper, brass, steel, or plastics (e.g., acrylics). The particular material to be used may depend, for example, upon a particular desired application such as various films made using the machined work piece. Actuator 38, and the actuators described below, can be implemented with stainless steel, for example, or other materials.

Actuator 38 is removably connected to a tool post 36, which is in turn located on a track 32. The tool post 36 and actuator 38 are configured on track 32 to move in both an x-direction and a z-direction as shown by arrows 40 and 42. Computer 12 is in electrical connection with tool post 36 and actuator 38 via one or more amplifiers 30. When functioning as a controller, computer 12 controls movement of tool post 36 along track 32 and movement of tool tip 44 via actuator 38 for machining work piece 54. If an actuator has multiple PZT stacks, it can use separate amplifiers to independently control each PZT stack for use in independently controlling movement of a tool tip attached to the stacks. Computer 12 can make use of a function generator 28 in order to provide waveforms to actuator 38 in order to machine various microstructures in work piece 54, as further explained below.

The machining of work piece 54 is accomplished by coordinated movements of various components. In particular, the system, under control of computer 12, can coordinate and control movement of actuator 38, via movement of tool post 36, along with movement of the work piece in the c-direction 53 and movement of tool tip 44 in one or more of the x-direction, y-direction, and z-direction, those coordinates being explained below. The system typically moves tool post 36 at a constant speed in the z-direction, although a varying speed may be used. The movements of tool post 36 and tool tip 44 are typically synchronized with the movement of work piece 54 in the c-direction (rotational movement as represented by line 53). All of these movements can be controlled using, for example, numerical control techniques or a numerical controller (NC) implemented in software, firmware, or a combination in computer 12.

The cutting of the work piece can include continuous and discontinuous cutting motion. For a work piece in roll form, the cutting can include a helix-type cutting (sometimes referred to as thread cutting) or individual circles around or about the roll. For a work piece in planar form, the cutting can include a spiral-type cutting or individual circles on or about the work piece. An X-cut can also be used, which involves a nearly straight cutting format where the diamond tool tip can traverse in and out of the work piece but the overall motion of the tool post is rectilinear. The cutting can also include a combination of these types of motions.

Work piece 54, after having been machined, can be used to make films having the corresponding microstructures for use in a variety of applications. Examples of those films include optical films, friction control films, and micro-fasteners or other mechanical microstructured components. The films are typically made using a coating process in which a polymeric material in a viscous state is applied to the work piece, allowed to at least partially cure, and then removed. The cured polymer material typically forms a substantially transparent substrate for the film, which will have substantially the opposite structures than those in the work piece. For example, an indentation in the work piece results in a protrusion in the resulting film. Work piece 54, after having been machined, can also be used to make other articles having discrete elements or microstructures corresponding with those in the tool. One particular process to make films from a microreplication tool or work piece is referred to as continuous cast and cure (3C), described in the following patents, all of which are incorporated herein by reference as if

fully set forth: U.S. Patent Nos. 4,374,077; 4,576,850; 5,175,030; 5,271,968; 5,558,740; and 5,995,690.

Cooling fluid 46 is used to control the temperature of tool post 36 and actuator 38 via lines 48 and 50. A temperature control unit 52 can maintain a substantially constant temperature of the cooling fluid as it is circulated through tool post 36 and actuator 38. Temperature control unit 52 can be implemented with any device for providing temperature control of a fluid. The cooling fluid can be implemented with an oil product, for example a low viscosity oil. The temperature control unit 52 and reservoir for cooling fluid 46 can include pumps to circulate the fluid through tool post 36 and actuator 38, and they also typically include a refrigeration system to remove heat from the fluid in order to maintain it at a substantially constant temperature. Refrigeration and pump systems to circulate and provide temperature control of a fluid are known in the art. In certain embodiments, the cooling fluid can also be applied to work piece 54 in order to maintain a substantially constant surface temperature of the material to be machined in the work piece.

FIG. 2 is a diagram illustrating a coordinate system for a cutting tool such as system 10. The coordinate system is shown as movement of a tool tip 62 with respect to a work piece 64. Tool tip 62 may correspond with tool tip 44 and is typically attached to a carrier 60, which is attached to an actuator. The coordinate system, in this exemplary embodiment, includes an x-direction 66, a y-direction 68, and a z-direction 70. The x-direction 66 refers to movement in a direction substantially perpendicular to work piece 64. The y-direction 68 refers to movement in a direction transversely across work piece 64 such as in a direction substantially perpendicular to an axis of rotation of work piece 64. The z-direction 70 refers to movement in a direction laterally along work piece 64 such as in a direction substantially parallel to the axis of rotation of work piece 64. The rotation of the work piece is referred to as the c-direction, as represented by arrow 53 shown in FIGS. 1 and 2. If the work piece is implemented in planar form, as opposed to roll form, then the y-direction and z-direction refer to movement in mutually orthogonal directions across the work piece in directions substantially perpendicular to the x-direction. A planar form work piece can include, for example, a rotating disk or any other configuration of a planar material.

The system 10 can be used for high precision, high speed machining. This type of machining must account for a variety of parameters, such as the coordinated speeds of the components and the work piece material. It typically must take into consideration the specific energy for a given volume of metal to be machined, for example, along with the thermal stability and properties of the work piece material. Cutting parameters relating to machining are described in the following references, all of which are incorporated herein by reference as if fully set forth: Machining Data Handbook, Library of Congress Catalog Card No. 66-60051, Second Edition (1972); Edward Trent and Paul Wright, Metal Cutting, Fourth Edition, Butterworth-Heinemann, ISBN 0-7506-7069-X (2000); Zhang Jin-Hua, Theory and Technique of Precision Cutting, Pergamon Press, ISBN 0-08-035891-8 (1991); and M. K. Krueger et al., New Technology in Metalworking Fluids and Grinding Wheels Achieves Tenfold Improvement in Grinding Performance, Coolant/Lubricants for Metal Cutting and Grinding Conference, Chicago, Illinois, U.S.A., June 7, 2000.

PZT Stack, Tool Tip Carrier, and Tool Tip

FIG. 3 is a diagram of an exemplary PZT stack 72 for use in a cutting tool. A PZT stack is used to provide movement of a tool tip connected to it and operates according to the PZT effect, which is known in the art. According to the PZT effect, an electric field applied to certain types of materials causes expansion of them along one axis and contraction along another axis. A PZT stack typically includes a plurality of materials 74, 76, and 78 enclosed within a casing 84 and mounted on a base plate 86. The materials in this exemplary embodiment are implemented with a ceramic material subject to the PZT effect. Three disks 74, 76, and 78 are shown for exemplary purposes only and any number of disks or other materials, and any type of shapes of them, can be used based upon, for example, requirements of particular embodiments. A post 88 is adhered to the disks and protrudes from casing 84. The disks can be implemented with any PZT material such as for example, a barium titanate, lead zirconate, or lead titanate material mixed, pressed, based, and sintered. The disks can also be implemented with a magnetostrictive material, for example.

Electrical connections to the disks 74, 76, and 78, as represented by lines 80 and 82, provide electrical fields to them in order to provide for movement of post 88. Due to

the PZT effect and based upon the type of electric field applied, precise and small movement of post 88, such as movement within several microns, can be accomplished. Also, the end of PZT stack 72 having post 88 can be mounted against one or more Belleville washers, which provides for preloading of the PZT stack. The Belleville washers have some flexibility to permit movement of post 88 and a tool tip attached to it.

FIGS. 4A-4D are views of an exemplary tool tip carrier 90, which would be mounted to post 88 of the PZT stack for control by an actuator, as explained below. FIG. 4A is a perspective view of tool tip carrier 90. FIG. 4B is a front view of tool tip carrier 90. FIG. 4C is a side view of tool tip carrier 90. FIG. 4D is a top view of tool tip carrier 90.

As shown in FIGS. 4A-4D, tool tip carrier 90 includes a planar back surface 92, a tapered front surface 94, and a protruding surface 98 with angled or tapered sides. An aperture 96 provides for mounting of tool tip carrier 90 onto a post of a PZT stack. Tapered surface 98 would be used for mounting of a tool tip for machining of a work piece. In this exemplary embodiment, tool tip carrier 90 includes a planar surface to enhance stability of mounting it by providing for more surface area contact when mounted to a PZT stack, and it includes the tapered front surfaces to reduce the mass of it. Tool tip carrier 90 would be mounted to post 88 of the PZT stack by use of an adhesive, brazing, soldering, a fastener such as a bolt, or in other ways.

Other configurations of tool tip carriers are possible based, for example, upon requirements of particular embodiment. The term "tool tip carrier" is intended to include any type of structure for use in holding a tool tip for machining a work piece. Tool tip carrier 90 can be implemented with, for example, one or more of the following materials: sintered carbide, silicon nitride, silicon carbide, steel, titanium, diamond, or synthetic diamond material. The material for tool tip carrier 90 preferably is stiff and has a low mass.

FIGS. 5A-5D are views of an exemplary tool tip 100, which would be secured to surface 98 of tool tip carrier 90 such as by use of an adhesive, brazing, soldering, or in other ways. FIG. 5A is a perspective view of tool tip 100. FIG. 5B is a front view of tool tip 100. FIG. 5C is a bottom view of tool tip 100. FIG. 5D is a side view of tool tip 100. As shown in FIGS. 5A-5D, tool tip 100 includes sides 104, tapered and angled front surfaces 106, and a bottom surface 102 for securing it to surface 98 of tool tip carrier 90.

The front portion 105 of tool tip 100 is used for machining of a work piece under control of an actuator. Tool tip 100 can be implemented with, for example, a diamond slab.

Interrupted Cut FTS Actuator

An interrupted cut FTS actuator can be used to make small microstructures as the tool tip is in discontinuous contact with work piece during cutting, creating non-adjacent microstructures. These features can be used to make film light guides, micro-fluidic structures, segmented adhesives, abrasive articles, optical diffusers, high contrast optical screens, light redirecting films, anti-reflection structures, light mixing structures, and decorative films.

The actuator can provide for other advantages. For example, the features can be made so small as to be invisible to the naked eye. This type of feature reduces the need for a diffuser sheet to hide the light extraction features in a liquid crystal display, for example. Another advantage is that the extraction features can be made linear or circular. In the linear case, they can be used with conventional cold cathode fluorescent lamp (CCFL) light sources, for example. In the circular case, the features can be made on circular arcs with a center point located where an LED would normally be positioned. Yet another advantage relates to programming and structure layout where all features need not lie along a single line as with a continuous groove. The area density of the light extraction features can be adjusted deterministically by arranging spacing along the features, spacing orthogonal to the features, and depth. Furthermore, the light extraction angle can be made preferential by selecting the angle and half angles of the cut facets.

The depth of the features may be in the region of 0 to 35 microns, for example, and more typically 0 to 15 microns. For a roll work piece, the length of any individual feature is controlled by the revolutions per minute (RPM) of the rotating work piece along the c-axis, and the response time of and waveform input to the FTS. The feature length can be controlled from 1 to 200 microns, for example. For a helix type cutting, the spacing orthogonal to the grooves (pitch) can also be programmed from 1 to 1000 microns. As illustrated below, the tool tip to make the features will taper-in and taper-out of the material, thereby creating structures, the shape of which are controlled by the RPM, the response time of and waveform input to the FTS, the resolution of the spindle encoder, and the clearance angle of the diamond tool tip (for example, a maximum of 45 degrees).

The clearance angle can include a rake angle of the tool tip. The features can have a wide variety of three-dimensional shapes such as, for example, symmetrical, asymmetrical, substantially hemispherical, prismatic, and semi-ellipsoidal.

FIGS. 6A-6H are views of an exemplary actuator 110 for use in implementing an interrupted cut microreplication system and process. The term "actuator" refers to any type of actuator or other device that provides for movement of a tool tip in substantially an x-direction for use in machining a work piece. FIG. 6A is a top sectional view of actuator 110. FIG. 6B is a front sectional view illustrating placement of a PZT stack in actuator 110. FIG. 6C is a front view of actuator 110. FIG. 6D is a back view of actuator 110. FIG. 6E is a top view of actuator 110. FIGS. 6F and 6G are side views of actuator 110. FIG. 6H is a perspective view of actuator 110. Some details of actuator 110 in FIGS. 6C-6H have been removed for clarity.

As shown in FIGS. 6A-6H, actuator 110 includes a main body 112 capable of holding an x-direction PZT stack 118. PZT stack 118 is attached to a tool tip carrier 136 having a tool tip 135 for using in moving the tool tip in an x-direction as shown by arrow 138. PZT stack 118 can be implemented with the exemplary PZT stack 72 shown in FIG. 3. The tool tip 135 on a carrier 136 can be implemented with the tool tip carrier shown in FIGS. 4A-4D and the tool tip shown in FIGS. 5A-5D. Main body 112 also includes two apertures 114 and 115 for use in removably mounting it to tool post 36, such as via bolts, for machining work piece 54 under control of computer 12.

PZT stack 118 is securely mounted in main body 112 for the stability required for precise controlled movement of tool tip 135. The diamond on tool tip 135 in this example is an offset 45 degree diamond with a vertical facet, although other types of diamonds may be used. For example, the tool tip can be V-shaped (symmetric or asymmetric), round-nosed, flat, or a curved facet tool. Since the discontinuous (non-adjacent) features are cut on a diamond turning machine, they can be linear or circular. Furthermore, since the features are not continuous, it is not required that they even be located along a single line or circle. They can be interspersed with a pseudo-randomness.

PZT stack 118 is secured in main body 112 by rails such as rails 120 and 122. The PZT stack 118 can preferably be removed from main body 112 by sliding it along the rails and can be secured in place in main body 112 by bolts or other fasteners. PZT stack 118 includes electrical connection 130 for receiving signals from computer 12. The end cap of

PZT stacks 118 includes a port 128 for receiving cooling fluid such as oil from reservoir 46, circulating it around the PZT stack, and delivering the oil back to reservoir 46, via port 132, for maintaining temperature control of it. Main body 112 can include appropriate channels for directing the cooling fluid around PZT stack 118, and the cooling fluid can be circulated by a pump or other device in temperature control unit 52.

FIG. 6B is a front sectional view illustrating placement of PZT stack 118 in main body 112 with the end cap of PZT stack 118 not shown. Main body 112 can include a plurality of rails in each aperture for the PZT stacks to hold them securely in place. For example, PZT stack 118 is surrounded by rails 120, 122, 142, and 144 in order to hold it securely in place when mounted in main body 112. The end cap attached to PZT stack 118 can accommodate bolts or other fasteners to secure PZT stack to one or more of the rails 120, 122, 142, and 144, and the end cap can also provide for sealing PZT stack 118 in main body 112 for use in circulating the cooling fluid around it. PZT stack 118 can include one or more Belleville washers positioned between the stacks and the tool tip carrier 136 for preloading of them.

FIGS. 7A-7C illustrate interrupted cut machining of a work piece using the exemplary actuator and system described above. In particular, FIGS. 7A-7C illustrate use of variable taper-in and taper-out angles of a tool tip, and those angles can be controlled using, for example, the parameters identified above. Each of FIGS. 7A-7C illustrate examples of the work piece before and after being cut with varying taper-in and taper-out angles. The taper-in angle is referred to as λ_{IN} and the taper-out angle is referred to as λ_{OUT}. The terms taper-in angle and taper-out angle mean, respectively, an angle at which a tool tip enters a work piece and leaves a work piece during machining. The taper-in and taper-out angles do not necessarily correspond with angles of the tool tip as it moves through a work piece; rather, they refer to the angles at which the tool tip contacts and leaves the work piece. In FIGS. 7A-7C, the tool tips and work pieces can be implemented, for example, with the system and components described above.

FIG. 7A is a diagram illustrating an interrupted cut 150 with substantially equal taper-in and taper-out angles into and out of a work piece 153. As shown in FIG. 7A, a taper-in angle 152 of a tool tip 151 into a work piece 153 is substantially equal to a taper-out angle 154 ($\lambda_{IN} \approx \lambda_{OUT}$). The duration of the tool tip 151 into work piece 153 determines a length L (156) of the resulting microstructure. Using substantially equal

taper-in and taper-out angles results in a substantially symmetrical microstructure 158 created by removal of material from the work piece by the tool tip. This process can be repeated to make additional microstructures, such as microstructure 160, separated by a distance D (162).

FIG. 7B is a diagram illustrating an interrupted cut with a taper-in angle less than a taper-out angle into and out of a work piece 167. As shown in FIG. 7B, a taper-in angle 166 of a tool tip 165 into a work piece 167 is less than a taper-out angle 168 ($\lambda_{IN} < \lambda_{OUT}$). The dwell time of the tool tip 165 in work piece 167 determines a length 170 of the resulting microstructure. Using a taper-in angle less than a taper-out angle results in an asymmetrical microstructure, for example microstructure 172, created by removal of material from the work piece by the tool tip. This process can be repeated to make additional microstructures, such as microstructure 174, separated by a distance 176.

FIG. 7C is a diagram illustrating an interrupted cut with a taper-in angle greater than a taper-out angle into and out of a work piece 181. As shown in FIG. 7C, a taper-in angle 180 of a tool tip 179 into a work piece 181 is greater than a taper-out angle 182 ($\lambda_{IN} > \lambda_{OUT}$). The dwell time of the tool tip 179 in work piece 181 determines a length 184 of the resulting microstructure. Using a taper-in angle greater than a taper-out angle results in an asymmetrical microstructure, for example microstructure 186, created by removal of material from the work piece by the tool tip. This process can be repeated to make additional microstructures, such as microstructure 188, separated by a distance 190.

In FIGS. 7A-7C, the dashed lines for the taper-in and taper-out angles (152, 154, 166, 168, 180, 182) are intended to conceptually illustrate examples of angles at which a tool tip enters and leaves a work piece. While cutting the work piece, the tool tip can move in any particular type of path, for example a linear path, a curved path, a path including a combination of linear and curved motions, or a path defined by a particular function. The path of the tool tip can be chosen to optimize cutting parameters such as total time to complete cutting the work piece.

FIG. 8 is a diagram conceptually illustrating microstructures in a film that can be made using the cutting tool system having an interrupted cut FTS actuator to make a machined work piece and using that work piece to make a structured film. As shown in FIG. 8, an article 200 includes a top surface 202 and a bottom surface 204. Top surface 202 includes interrupted cut protruding microstructures such as structures 206, 208, and

210, and those microstructures can be made using the actuators and system described above to machine a work piece and then using that work piece to make a film or article using a coating technique. In this example, each microstructure has a length L, the sequentially cut microstructures are separated by a distance D, and adjacent microstructures are separated by a pitch P. Examples of an implementation of those parameters are provided above.

Machined Tool Tips

FIGS. 9A-9D are views of an exemplary machined tool tip 220, which would be secured to surface 98 of tool tip carrier 90 such as by use of an adhesive, brazing, soldering, or in other ways. FIG. 9A is a perspective view of tool tip 220. FIG. 9B is a front view of tool tip 220. FIG. 9C is a bottom view of tool tip 220. FIG. 9D is a side view of tool tip 220. As shown in FIGS. 9A-9D, tool tip 220 includes sides 224, tapered and angled front surfaces 226, and a bottom surface 222 for securing it to surface 98 of tool tip carrier 90. The front portion 225 of tool tip 220 is used for machining of a work piece under control of an actuator, for example by using the system described above. Tool tip 220 is machined in that it also has microstructures (e.g., grooves) 221 and 223 on front portion 225, and the microstructures 221 and 223 are also used for machining of a work piece. The microstructures in the machined tool tip can have one or more of those exemplary shapes and dimensions identified above.

Tool tip 220 can be implemented with, for example, a diamond slab. The microstructures 221 and 223, as well as other microstructures on machined tool tips, can be made preferably via ion milling. Other techniques to make microstructures or diffractive structures on tool tips include micro electrical discharge machining, grinding, lapping, ablation, laser milling, photolithography followed by etching, or other ways to impart scratches or features into the tool tip. Another technique to make microstructures or diffractive structures on tool tips includes machining the inverse of the intended structure in a mold that is more easily machineable than diamond and then forming the hard tool machine tool by filling the mold with either plasma deposited material, or using fine powder under high pressure in the mold to form a solid.

Alternatively, diamonds can be lapped in a traditional fashion and bonded precisely together to make a macro tool assembly having microstructured features. Only

one microstructure is shown on each side of the tool tip for illustrative purposes only; the tool tip can have any number of microstructures and any shape, dimension, and configuration of them. As an alternative to an indenting microstructure, machined tool tips can have protruding microstructures, or a combination of indenting and protruding microstructures.

It is possible to mount more than one tool tip to a tool tip carrier, such as carrier 90, for machining of a work piece. In those embodiments, the multiple tool tips machine a work piece to essentially simultaneously make microstructures in it, such as parallel microstructured grooves or other features. FIG. 10A is a side view of an exemplary multi-tip tool 230 having machined and non-machined tool tips. The term "non-machined" tool tip refers to a tool tip that, once having been created through machining, is not subjected to additional machining that would be used to make microstructures in the tool tip. Multi-tip tool 230 has a non-machined tool tip 234 and a machined tool tip 236 with microstructures 238. Tool tips 234 and 236 are mounted to a base 232 such as surface 98 of tool tip carrier 90, and they can be mounted using, for example, adhesive, brazing, soldering, or in other ways. The distance 240 between tool tips 234 and 236 determines a pitch of the corresponding microstructures machined with multi-tip tool 230 with the microstructure corresponding with tool tip 236 having additional microstructures machined within it.

In FIGS. 10-24, the term "side view" is used as a matter of convenience. Although referred to as side views, these views illustrate what would be viewed as the top of tool tips when looking down on them during the machining process.

FIG. 10B is a side view of a multi-tip tool 242 having multiple machined tool tips. Multi-tip tool 242 has a machined tool tip 246 with microstructures 248 and another machined tool tip 250 with microstructures 252. Tool tips 246 and 250 are mounted to a base 244 such as surface 98 of tool tip carrier 90, and they can be mounted using, for example, adhesive, brazing, soldering, or in other ways. The distance 254 between tool tips 246 and 250 determines a pitch of the corresponding microstructures machined with multi-tip tool 242 with the microstructures corresponding with tool tips 246 and 250 each having additional microstructures machined within it corresponding with microstructures 248 and 252, respectively.

In FIGS. 10A and 10B, only two tool tips are shown for illustrative purposes only; a multi-tip tool can have any number of tool tips. The multiple tool tips, when machined, can have the same or different microstructures, and those individual microstructures can have one or more of those exemplary shapes and dimensions identified above. The distance (pitch 240 and 254) between the tool tips in a multi-tip tool can include a 1000 micron pitch, 100 micron pitch, 1 micron pitch, or even a sub-optical wavelength pitch around 200 nm. Alternatively, in other embodiments, the pitch between the tool tips in a multi-tip tool can be greater than 1000 microns. In a multi-tip tool have more then two tool tips, the pitch between adjacent tool tips can be the same or different. These dimensions are provided for illustrative purposes only, and microstructures made using the actuators and system described in the present specification can have any dimension within the range capable of being tooled using the system.

Work piece 54 can be machined using any of the machined tool tips or multi-tips tools, and the machined work piece can be used to make films as described above. The work piece can be machined in a continuous cutting or interrupted cutting using the system and process described above, for example. FIGS. 11A and 11B are side and perspective views, respectively, conceptually illustrating microstructures that can be made using the cutting tool system having an FTS actuator with at least one machined tool tip. As shown in FIGS. 11A and 11B, a work piece 260 has a continuous machined microstructure 262 (e.g., a groove) having machined microstructures 263 and 264 (e.g., ridges) within it as caused by the microstructures in a corresponding machined tool tip.

FIGS. 12A and 12B are side and perspective views, respectively, conceptually illustrating microstructures that can be made using the cutting tool system having an interrupted cut FTS actuator with at least one machined tool tip. As shown in FIGS. 12A and 12B, a work piece 270 has a discontinuous (interrupted cut) machined microstructure 272 (e.g., a feature not contiguous with other machined features) having machined microstructures 273 and 274 (e.g., ridges) within it as caused by the microstructures in a corresponding machined tool tip. The interrupted cutting using one or more machined tool tips can vary the taper-in and taper-out angles of the tool tip into and out of a work piece as described above and shown in FIGS. 7A-7C.

Work pieces 260 and 270 can then be used in a coating technique, as described above, to make films or other articles having the opposite microstructures corresponding with the microstructures in work pieces 260 and 270.

Machined Tool Tips with Diffractive Features

FIGS. 13A, 13B, 14, 15A, 15B, and 16-22 are views of exemplary machined tool tips having diffractive features, and these tool tips would be secured to surface 98 of tool tip carrier 90 such as by use of an adhesive, brazing, soldering, or in other ways. FIGS. 23A, 23B, 24A, and 24B are diagrams illustrating methods to fabricate tool tips to form diffractive features in them. The features shown on the tool tips in FIGS. 13A, 13B, 14, 15A, 15B, and 16-22 are not shown to scale. Rather, the tool tips shown in FIGS. 13A, 13B, 14, 15A, 15B, and 16-22 are intended to show examples of shapes and configurations of features to provide for diffraction, and the features can have any dimension and spacing depending upon, for example, an amount of diffraction desired from the features. Aside from the diffractive features, the tool tips shown in FIGS. 13A, 13B, 14, 15A, 15B, and 16-22 can have, for example, the same general shape and configuration as tool tip 100 having two facets, front surfaces 106, optionally with the tapered front portion 105.

In some embodiments, diffractive features refer to features in a film or article causing diffraction of light or to features in a tool that, when used to make a film or article, result in diffractive features in the film or article. As described above, the film or article having the diffractive features are made from a machined tool having the corresponding diffractive features. The diffractive features can be tuned to obtain a desired amount of diffraction in a film or article made from the machined tool. In particular, the size and shape of the diffractive features, along with the spacing between the diffractive features, can be designed for the amount or degree of diffraction of light desired for a particular application. For example, as the spacing between the features decreases, the features cause increasing diffraction of light. Therefore, features spaced farther apart cause less diffraction, and features spaced more closely together cause more diffraction. In certain embodiments, for example, the diffractive features, such as grooves, can be spaced within 10 microns, 5 microns, 1 micron, or within a distance near a particular wavelength of light. In one embodiment, the diffractive features include multiple features having a substantially triangular cross-sectional shape and having a spacing of 650 nm between

them. For example, one embodiment includes 28 such features each spaced approximately 650 nm apart. In some embodiments, diffractive features refer to nano-scale features. For example, the diffractive features can have a size on the order of 100 nm or even as small as 10 nm. The size of the diffractive features on the tool tip results in substantially the same size of diffractive features in films, as illustrated below, made from a work piece machined with a diffractive tool tip.

In other embodiments, diffractive features refer to features having dimensions in or approximate the ranges described for optical applications and as used in a film or article for non-optical applications such as hydrophobicity, microfluidic capillary action, friction control films, micro-fasteners, or other mechanical microstructured components.

In certain embodiments, films made from tools machined as described in the present specification will have a particular signature indicating that they were made from such tools. In particular, in some embodiments a multi-tip tool (e.g., tools 230 and 242) is used for continuous cutting of one or more passes around the tool (work piece 54). The distance between the diffractive features or grooves made by tips on the tool (e.g., distances 240 and 254) are substantially constant as the tips are held a constant distance apart by the tool base (e.g., bases 232 and 244). The tool is moved along the face of the work piece at an approximately constant speed in the z-direction by a linear motor. However, the speed is not exactly constant because the linear motor occasionally moves the tool slightly backward or forward at a speed slightly more than the nominal speed due to noise in the servo system. These variations in speed result in occasional variations in the distance between grooves. A typical variation in one particular application was approximately plus or minus 0.2 microns. Repeatedly aligning a tool tip at a constant distance adjacent previously cut features can be difficult and is not required for many applications. A film made from a tool cut in this manner will thus have a repeating set of diffractive features or grooves with a substantially constant distance corresponding with the distance between the tips on the multi-tip tool (e.g., distances 240 and 254), and it will have a randomly repeating variable distance between the sets of diffractive features or grooves resulting from small variations in the speed of the tool in the z-direction.

The tools shown in FIGS. 13A, 13B, 14, 15A, 15B, and 16-22, 23A, 23B, 24A, and 24B can be implemented with, for example, a diamond slab. The diffractive features on the tool tips can be made preferably via ion milling. Other techniques to make diffractive

features on tool tips include micro electrical discharge machining, grinding, lapping, ablation, or other ways to impart scratches or features into the tool tip. Alternatively, diamonds can be lapped in a traditional fashion and bonded precisely together to make a macro tool assembly having diffractive features. As an alternative to an indenting diffractive feature, machined tool tips can have protruding diffractive features, or a combination of indenting and protruding diffractive features.

Work piece 54 can be machined using any of the exemplary tool tips shown in FIGS. 13A, 13B, 14, 15A, 15B, and 16-22, 23B and 24B, and the machined work piece can be used to make films as described above. The work piece can be machined in a continuous cutting or interrupted cutting using the system and process described above, for example, to machine diffractive features into the work piece. The machined work piece or tool can then be used to make films, as described above, having corresponding diffractive features. These films can be made to have unique diffractive and refractive optical power. An exemplary purpose of the these unique diffractive and refractive optical forms in enhancement films is to provide more options for moving light out of the central viewing zone with more versatility than simply putting a radius on the tip of a tool.

The master tool can be achieved through plunge or thread cutting with the ion milled diamond, as described above. Plunge and thread cutting are described in U.S. Patent Nos. 7,140,812 and 6,707,611, which are incorporated herein by reference as if fully set forth. In films made from the master tool machined with these tool tips, the features do not have to be present on every groove of the films. For example, multi-start thread or plunge cutting can be used to interleave grooves cut with both conventional diamonds and ion milled diamonds. The ion milled diffractive features can be present on only one of the two facets of a typical symmetric prism angle, for example, 90°. This type of tool tip allows for finer optical tuning of the luminance profile. The ion milled diffractive features facilitate a smoother cut-off, or luminance profile, in optical films such as BEF. The ion milled features can also facilitate cutting time reduction for optical film when multiple tool tips are used.

FIG. 13A is a side view of a tool tip 300 with diffractive features 302 and 304 on both facets. The diffractive features 302 and 304 are shown as V-grooves or notches in this example. The grating spacing 303 between diffractive features can be constant or varied to produce different properties that would be of value or interest. For example, by

varying the grating spacing, one could smooth the divergence profile in corresponding optical films as compared to a constant grating spacing. This spacing can also help with wavelength dependence and ameliorate color effects. The shape of the ion milled grating does not have to be V-shaped, although negative draft angles should typically be avoided. The width and depth of the grating grooves or notches will usually be less than one micron but could be greater than one micron. There are many shapes which could be utilized to produce the notches or grooves. For visible light applications, the distance 303 between grating grooves will usually be in the 0.5 micron to 10 micron spacing range, although other ranges may be used to meet design goals.

A diamond tool was produced using this design with the diffractive features 302 and 304 being 5 microns apart (distance 303) and with each diffractive feature having a width of 1 micron across the groove. In this case, the diffractive grooves were shown to provide controlled scattering of the light away from the region of refractive, transmitted maxima which cut off at approximately 31° in the film samples. The diffractive features of this film were shown to smoothly broaden the luminance profile using photometric measurements with a goniometer. The luminance profile can be tuned by making the grating spacing greater and reducing the number of grooves or features. Alternatively, decreasing the grating spacing and increasing the number of grooves or features can also be used to fine tune the profile.

FIG. 13B is a side view of a tool tip 301 with diffractive features 305 and 307 on both facets. Tool tip 301 is a variation of the configuration of tool tip 300 in that the diffractive features 305 and 307 are separated by curved portions rather than flat portions.

The examples of ion milled diamond forms, described below for FIGS. 14-22, illustrate other embodiments for tuning the luminance profile.

FIG. 14 is a side view of a tool tip 306 with diffractive features 308 on one facet and no features on the other facet 310. Diffractive features 308 may comprise V-grooves or notches and have a constant or variable grating spacing.

FIG. 15A is a side view of a tool tip 312 with diffractive features 314 using a step height variation 313, which may be constant or varying among the features.

FIG. 15B is a side view of a tool tip 309 with diffractive features 311 using a step height variation 315, which may be constant or varying among the features. Tool tip 309 is a variation of the configuration of tool tip 312 in that the diffractive features 311 have a

single angled step height variation rather than step height variations on both sides of the diffractive features.

FIG. 16 is a side view of a tool tip 316 with diffractive features 320 and 322 along 90° (318) facet sides 317 and 319. Diffractive features 320 and 322 can be near the tip or near the valley (away from the tip) as appropriate to the design or as desired. Also, the diffractive features 320 and 322 can be located arbitrarily along the 90° facet walls.

FIG. 17 is a side view of a tool tip 323 with diffractive features 324 along a flat tip 325. In one example, this type of configuration of diffractive features on a tool tip was made from a diamond having a 10 micron width (325) with 11 V-grooves (324) spaced 1 micron apart.

FIG. 18 is a side view of a tool tip 326 with diffractive features 328 along a curved tip 327.

FIG. 19 is a side view of a tool tip 330 with diffractive features 332 formed in steps having a height 333 along 90° facets, for example.

FIG. 20 is a side view of a tool tip 334 with diffractive features 336 having a lenticular shape along a substantially flat portion of the tool tip.

FIG. 21 is a side view of a tool tip 338 with diffractive features along curved facets 340 formed from adjacent concave and convex portions along the facets.

FIG. 22 is a side view of a tool tip 342 with diffractive features along multiple linear facets 344 formed from adjacent angular flat portions along the facets.

FIGS. 23A and 23B illustrate a method of ion milling a tool tip to create diffractive features. FIG. 23A is a side view of a tool tip 350 before ion milling. Tool tip 350 can be implemented with a diamond slab, for example, and it has facets 352 and 354, and a flat tip 356. FIG. 23B is a side view of tool tip 350 after using ion milling to form diffractive features in the same plane on the tip. In particular, ion milling of the flat tip 356 at its center point produces a valley 358 to create two diffractive features 360 and 362 having points lying in substantially the same plane 364.

FIGS. 24A and 24B illustrate another method of ion milling a tool tip to create diffractive features. FIG. 24A is a side view of a tool tip 370 before ion milling. Tool tip 370 can be implemented with a diamond slab, for example, and it has facets 372 and 374, and a flat tip 376. FIG. 24B is a side view of the tool tip of FIG. 24A after using ion milling to form diffractive features in different planes on the tip. In particular, ion milling

of the flat tip 376 at an off-center point produces a valley 378 to create a first diffractive feature 380 having a point lying in a plane 386 and a second diffractive feature 382 having a point lying in a plane 384 different from plane 386. The process to make the diffractive features shown in FIGS. 23B and 24B can be repeated to make several diffractive features on the tool tip, and the features shown in FIGS. 23B and 24B are not shown to scale; rather, they are intended to illustrate processes for making diffractive features on tool tips.

The use of tool tips with diffractive features as described above to make microreplicated articles, such as films, can provide for many advantageous or desirable features. For example, they can be used in light management applications for light direction, softening cutoff angles, extraction of light for light guides, or decorative effects on existing features such as rainbow effects on interrupted cut lenslets. Also, a diffractive feature on a larger microstructure provides for an additional degree of freedom for redirecting light.

The tool tips described above can be used to make features on a macro-scale (dimensions of 1 micron and above) and a nano-scale (dimensions less than 1 micron), and the features can be made using one or more tool tips in a continuous or interrupted cut mode. In addition, the cutting using the tool tips can be accomplished in an x-direction, a y-direction, or a z-direction into the tool, or a combination of those directions. For example, the features can be cut using the tool tip with multiple actuators. Systems to use multiple actuators for cutting a tool are described in U.S. Patent Applications Serial Nos. 11/274723, 11/273875, 11/273981, and 11/273884, all of which were filed November 15, 2005 and all of which are incorporated herein by reference as if fully set forth. Alternatively, the diffractive features can be cut in the tool without use of an actuator, which can involve continuous cutting with the tool tip(s) held at a substantially constant or a non-constant depth in the surface of the tool using, for example, a low frequency servo.

Non-FTS Machining with Diffractive Tool Tips

As an alternative to machining using an FTS actuator, a work piece can machined using a non-FTS tool post in which the tool tip is held into the work piece at a substantially constant depth and moved along the work piece to machine features in a substantially helical pattern. In this embodiment, the tool tip has one or more diffractive features, and at least one of those features is in contact with the work piece during the

machining of it. As described above, this machining allows for the creation of macro-scale features having diffractive features. The machined work piece can then be used to make films, such as optical films, having the corresponding features.

FIGS. 25A-25C are views of an exemplary non-FTS tool post 400. FIGS. 25A and 25B are perspective views of tool post 400. FIG. 25C is a top view of tool post 400. As shown in FIGS. 25A-25C, tool post 400 includes a base 402, a vertical portion 404 attached to base 402, and a top 410 attached to an end of vertical portion 404 opposite base 402. Top 410 includes apertures 416 and 418 for securing it to vertical portion 404 via bolts or other fasteners. A block 412 is located on top 410 and has apertures 420 and 422 for securing it to top 410 via bolts or other fasteners. A shank 414 holds a tool tip for machining work piece 54, and shank 414 is held securely on top 410 via friction between block 412 and top 410. By removing and resecuring block 412, a position of shank 414 in an x-direction into work piece 54 can be adjusted, as illustrated by arrow 424 (see FIG. 25C). Base 402 has apertures, such as apertures 406 and 408, for attaching tool post 400 to track 32 via bolts or other fasteners. Alternatively, one or more other posts or structures can be attached between track 32 and base 402 of tool post 400. During machining, tool post 400 is configured and positioned such that work piece 54 does not contact base 402 when the tool tip is held into work piece 54. When attached to track 32, tool post 400 can hold a tool tip on shank 414 into work piece 54, and the tool tip can be moved along work piece 54 by moving tool post 400 in a z-direction along track 32 under control of computer 12 while work piece 54 is rotated under control of drive unit and encoder 56. The components of tool post 400 can be implemented with stainless steel, for example, or other materials.

FIGS. 26A-26D are views of exemplary shank 414. FIG. 26A is a perspective view of shank 414. FIG. 26B is a front view of shank 414. FIG. 26C is a bottom view of shank 414. FIG. 26D is a side view of shank 414. As shown in FIGS. 26A-26D, shank 414 includes sides 430, tapered and angled front surfaces 432 on a front portion 434, a bottom surface 438, and a protruding surface 436 for mounting a tool tip and having angled or tapered sides. A tool tip would be mounted to surface 436 of shank 414 by use of an adhesive, brazing, soldering, or in other ways. The tool tip secured to shank 414 preferably includes a tool tip with diffractive features, such as the tool tips shown in FIGS. 13-22 and implemented with the exemplary tool tip materials provided above, for use in

machining diffractive features into work piece 54. Shank 414 can be implemented with, for example, one or more of the following materials: sintered carbide, silicon nitride, silicon carbide, steel, titanium, diamond, or synthetic diamond material.

Optical Films with Diffractive Features

Microreplication master tools or work pieces can be fabricated using tool tips with diffractive features in a machining process as described above. Those tool tips include, for example, the tool tips shown in FIGS. 13A, 13B, 14, 15A, 15B, and 16-22. Combining this tooling capability with microreplication processes such as 3C, identified above, enable the formation of optical films having, on a major surface of the film substrate, microreplicated macro-scale features and one or more microreplicated diffractive features on the macro-scale features. The terms "macro-scale features" and "diffractive features" are defined above.

The substrate is typically formed integral or monolithic with the macro-scale features in a 3C process or using thermoplastic replication, for example. Alternatively, the substrate can have multiple layers with one of the layers formed integral with the features. The films can be flexible or rigid when cured.

The diffractive features provide for greater versatility in the optical performance of the films. For example, the macro-scale features can recycle light while the diffractive features can diffuse light in order to provide for a single film that functions as both a brightness enhance film and a diffuser in a liquid crystal display (LCD) device or other backlit devices. The films can also be used to hide extraction features in a backlight system. Thus, the combination of macro-scale and diffractive features provide for greater light management in optical films.

FIGS. 27A, 27B, 28, 29A, 29B, and 30-36 illustrate representative portions of films made from work pieces machined with tool tips corresponding with the tool tips shown in FIGS. 13A, 13B, 14, 15A, 15B, and 16-22, respectively. These film portions are intended to represent the general shape and configuration of the macro-scale and diffractive features, and the films can have any number of substantially the same microreplicated macro-scale and diffractive features repeated throughout the film. The dimension of the films, length and width of the major surface, can be based upon, for example, an intended use of the films. The pitch between the macro-scale features can be

constant or varying, and the depth between the macro-scale features can also be constant or varying. A varying pitch and depth between macro-scale features, or one parameter varying with the other held constant, can be accomplished by machining using an X-Z actuator as disclosed in U.S. Patent No. 7,293,487, which is incorporated herein by reference as if fully set forth. Also, the macro-scale features can have a random, pseudo-random, or non-random configuration.

Each of the films illustrated in FIGS. 27A, 27B, 28, 29A, 29B, and 30-36 can be combined with the same or other films for a two film construction in which the macro-scale features of the two films are arranged at an angle to one another, preferably orthogonal to one another. One of the other films in the stacked configuration can be another film with macro-scale and diffractive feature, or alternatively it can be a film with other types of structures. For example, anti-moire, anti-wetout prism films are described in U.S. Provisional Patent Application Serial No. 60/974245, filed September 21, 2007, which is incorporated herein by reference as if fully set forth. The use of two films in a display device, for example, provides even greater versatility of light management.

The work pieces used to make the films can be machined with the diffractive tool tips using an FTS actuator or non-FTS machining as described above. The films can be made from a work piece having been machined with diffractive tool tips in a continuous cutting process, resulting in continuous macro-scale features in the film, or with interrupted cutting, resulting in discontinuous macro-scale features in the film. Continuous and interrupted cut machining are described above. If interrupted cutting is used to machine the work piece, the films illustrated in FIGS. 27A, 27B, 28, 29A, 29B, and 30-36 would have the corresponding macro-scale features formed as lenslets as shown in FIG. 8 with the addition of the diffractive features in the macro-scale lenslets.

The films made from work pieces machined with diffractive tool tips are preferably made with a substantially optically transmissive material, preferably substantially transmissive to visible light. Examples of materials to make the films include the following: polycarbonate; acrylic; polyethylene terephthalate (PET); polyvinyl chloride (PVC); polysulfone; 2,6-polyethylene naphthalate (PEN) or a co-polymer derived from ethylene glycol; naphthalene dicarboxylic acid and some other acids such as terephthalate (co-PEN); and other suitable materials. Other materials to make the films include useful oligomeric resin compositions which cure to a flexible state,

including, but not limited to, acrylate, epoxy, or urethane based materials, and preferably acrylate based materials. As used herein, the term "acrylate" encompasses methacrylate.

FIG. 27A is a perspective view illustrating a representative portion of a film 450 made from a work piece machined with a tool tip corresponding with the tool tip 300 shown in FIG. 13A. Film 450 has diffractive features 454 on macro-scale features 452. In film 450, the macro-scale features 452 include prisms, and the diffractive features 454 include one or more triangular notches on both facets of the prisms.

The films include a substrate, represented by portion 451 in film 450, providing a base for the macro-scale features. Substrate 451 can have any particular height as represented by distance 456, and the macro-scale features can also have any particular height, as represented by distance 458. The pitch between the macro-scale features, represented by distance 462, can have any particular value, and the pitch between the diffractive features, represented by distance 460, can also have any particular value. The films described below can likewise have any particular dimensions of the substrate and features, and any particular values for the pitch between the macro-scale features and the pitch between the diffractive features.

In addition, the macro-scale and diffractive features can vary from what is shown in FIGS. 27A, 27B, 28, 29A, 29B, and 30-36, which are intended to illustrate examples of films having diffractive features on macro-scale features. For example, the diffractive features do not need to be identical along a facet of the macro-scale features, neither do the facets need to be symmetrical. Each macro-scale and diffractive feature can be unique in shape and dimensions. Also, one or both of the facets of the macro-scale features can alternatively have an overall curved shape with or without diffractive features.

FIG. 27B is a perspective view illustrating a representative portion of a film 463 made from a work piece machined with a tool tip corresponding with the tool tip 301 shown in FIG. 13B. Film 463 has diffractive features 466 on macro-scale features 464. In film 463, the macro-scale features 464 include prisms, and the diffractive features 466 include a series of adjoining lenslets on both facets of the prisms.

FIG. 28 is a perspective view illustrating a representative portion of a film 467 made from a work piece machined with a tool tip corresponding with the tool tip 306 shown in FIG. 14. Film 468 has diffractive features 470 on macro-scale features 468. In

film 467, the macro-scale features 468 include prisms, and the diffractive features 470 include one or more triangular notches on only one facet of the prisms.

FIG. 29A is a perspective view illustrating a representative portion of a film 472 made from a work piece machined with a tool tip corresponding with the tool tip 312 shown in FIG. 15A. Film 472 has diffractive features 476 on macro-scale features 474. In film 472, the macro-scale features 474 include prisms, and the diffractive features 476 include a grating with a series of raised portions on both facets of the prisms.

FIG. 29B is a perspective view illustrating a representative portion of a film 478 made from a work piece machined with a tool tip corresponding with the tool tip 309 shown in FIG. 15B. Film 478 has diffractive features 482 on macro-scale features 480. In film 478, the macro-scale features 480 include prisms, and the diffractive features 482 include a grating with a series of angled portions on both facets of the prisms.

FIG. 30 is a perspective view illustrating a representative portion of a film 484 made from a work piece machined with a tool tip corresponding with the tool tip 316 shown in FIG. 16. Film 484 has diffractive features 488 on macro-scale features 486. In film 484, the macro-scale features 486 include prisms, and the diffractive features 488 include one or more triangular notches on both facets of the prisms along with a flat portion between the notches and the vertices of the prisms.

FIG. 31 is a perspective view illustrating a representative portion of a film 490 made from a work piece machined with a tool tip corresponding with the tool tip 323 shown in FIG. 17. Film 490 has diffractive features 494 on macro-scale features 492. In film 490, the macro-scale features 492 include prisms, and the diffractive features 494 include one or more triangular notches on flat vertices of the prisms.

FIG. 32 is a perspective view illustrating a representative portion of a film 496 made from a work piece machined with a tool tip corresponding with the tool tip 326 shown in FIG. 18. Film 496 has diffractive features 500 on macro-scale features 498. In film 496, the macro-scale features 498 include prisms, and the diffractive features 500 include one or more triangular notches on curved vertices of the prisms.

FIG. 33 is a perspective view illustrating a representative portion of a film 502 made from a work piece machined with a tool tip corresponding with the tool tip 330 shown in FIG. 19. Film 502 has diffractive features 506 on macro-scale features 504. In film 502, the macro-scale features 504 include prisms, and the diffractive features 506

include a series of adjoining steps on both facets of the prisms.

FIG. 34 is a perspective view illustrating a representative portion of a film 508 made from a work piece machined with a tool tip corresponding with the tool tip 334 shown in FIG. 20. Film 508 has diffractive features 512 on macro-scale features 510. In film 508, the macro-scale features 510 include prisms, and the diffractive features 512 include a series of adjoining lenslets on flat vertices of the prisms.

FIG. 35 is a perspective view illustrating a representative portion of a film 514 made from a work piece machined with a tool tip corresponding with the tool tip 338 shown in FIG. 21. Film 514 has diffractive features 518 on macro-scale features 516. In film 514, the macro-scale features 516 include prisms, and the diffractive features 518 include a series of adjoining curved portions on both facets of the prisms.

FIG. 36 is a perspective view illustrating a representative portion of a film 520 made from a work piece machined with a tool tip corresponding with the tool tip 342 shown in FIG. 22. Film 520 has diffractive features 524 on macro-scale features 522. In film 520, the macro-scale features 522 include prisms, and the diffractive features 524 include a series of adjoining angled flat portions on both facets of the prisms.

While the present invention has been described in connection with an exemplary embodiment, it will be understood that many modifications will be readily apparent to those skilled in the art, and this application is intended to cover any adaptations or variations thereof. For example, various types of materials for films, dimensions of the macro-scale and diffractive features, and configurations and shapes of the macro-scale and diffractive features may be used without departing from the scope of the invention. This invention should be limited only by the claims and equivalents thereof.

What is claimed is:

1. An optical film, comprising:

a substrate;

a plurality of microreplicated macro-scale features formed on a major surface of the substrate; and

one or more microreplicated diffractive features formed on the macro-scale features,

wherein the substrate and the macro-scale features are formed of a substantially light transmissive material.

2. The optical film of claim 1, wherein the macro-scale features comprise prisms having opposing facets and vertices.

3. The optical film of claim 2, wherein the diffractive features comprise triangular notches on at least one of the facets of the prisms.

4. The optical film of claim 2, wherein the diffractive features comprise triangular notches on only one of the facets of the prisms.

5. The optical film of claim 2, wherein the diffractive features comprise a series of adjoining lenslets on at least one of the facets of the prisms.

6. The optical film of claim 2, wherein the diffractive features comprise a grating with a series of raised portions on at least one of the facets of the prisms.

7. The optical film of claim 2, wherein the diffractive features comprise a grating with a series of angled portions on at least one of the facets of the prisms.

8. The optical film of claim 2, wherein the diffractive features comprise one or more triangular notches on at least one of the facets of the prisms along with a flat portion between the notches and the vertices of the prisms.

9. The optical film of claim 2, wherein the diffractive features comprise triangular notches on the vertices of the prisms, and wherein the vertices are flat.

10. The optical film of claim 2, wherein the diffractive features comprise triangular notches on the vertices of the prisms, and wherein the vertices are curved.

11. The optical film of claim 2, wherein the diffractive features comprise a series of adjoining steps on at least one of the facets of the prisms.

12. The optical film of claim 2, wherein the diffractive features comprise a series of adjoining lenslets on the vertices of the prisms, and wherein the vertices are flat.

13. The optical film of claim 2, wherein the diffractive features comprise a series of adjoining curved portions on at least one of the facets of the prisms.

14. The optical film of claim 2, wherein the diffractive features comprise a series of adjoining angled flat portions on at least one of the facets of the prisms.

15. The optical film of claim 1, wherein the macro-scale features are continuous.

16. The optical film of claim 1, wherein the macro-scale features are discontinuous.

17. The optical film of claim 1, wherein the macro-scale features have a constant pitch.

18. The optical film of claim 1, wherein the macro-scale features have a variable pitch.

19. An optical film, comprising:

a substrate;

a plurality of microreplicated macro-scale features formed on a major surface of the substrate, wherein the macro-scale features function to recycle visible light when the film is placed in a backlight; and

one or more microreplicated diffractive features formed on the macro-scale features, wherein the diffractive features function to diffuse visible light when the film is placed in a backlight,

wherein the substrate and the macro-scale features are formed of a substantially light transmissive material.

20. The optical film of claim 19, wherein the macro-scale features comprise prisms having opposing facets and vertices, and wherein the diffractive features comprise triangular notches on at least one of the facets of the prisms.