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MICRO RADIAL GRATING DISK MANUFACTURED BY NANOIMPRINTING TECHNIQUE FOR TRANSMISSION ERROR MEASUREMENT OF MICRO GEARS

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ABSTRACT

Nanoimprinting technique is applied for manufacturing a micro radial grating disk for a micro rotary enocder with a small diameter suitable for practical measurement application of micro gears. The number of gratings is up to 10,000, and an inner half pitch of the grating disk is corresponding to about 50nm. The nanoimprint process was successfully carried out with a single silicon master mold. The result shows that it is possible to manufacture grating disks of which diameters are smaller than 1mm as mass production. Although there are many issues to be overcome to realize a high precision micro rotary encoder, rotary encoders have great advantages such as robustness against temperature changes, possible error compensation, and applicable self-calibration technique.

Key Words – Nanoimprint, rotary encoder, micro gear, transmission error, measurement

1. INTRODUCTION

Micro gear is one of interesting micro machine elements for micro mechanisms in the next generation. It is used to transmit rotational motion in high accuracy without delay motion. In addition, the progress of microelectro-mechanical systems brings us the new stage of nanomanufacturing [1,2]. Micro gears have also been manufactured in this process nowadays [3]. To realize a miniature transmission system, measurement of gear accuracy is essential for evaluation of manufacturing errors, meshing status, and running performance [4].

Gears have originally concave parts as tooth spaces, and they must be measured with the non-destructive method. For micro gear systems, there are some unique difficulties. For example, in tooth surface topography measurement, a contact type or an optical stylus could not reach deeply inside a tooth space because the adjacent tooth interferes with the stylus going. To overcome the difficulty, it will be possible to measure the gear meshing accuracy, which is called transmission error, directly without knowing the tooth flank accuracy of a single gear. In transmission error measurement, the rotational angle of the shaft of each gear is measured with a rotary encoder [5]. For micro gear engagement, the center distance between a pair of gears is very small, so the rotary encoders have to be small as well as micro gears to avoid the interference between each rotary encoder and the rotational shaft of the mating gear side.

This paper focuses on nanomanufacturing of a micro radial grating disk for a micro rotary enocder with a small diameter suitable for practical measurement application of micro gears. The number of gratings will be up to 10,000, and an inner half pitch of the grating disk is corresponding to about 50nm. In addition, nanoimprinting technique is also applied to achieve low production cost per grating disk by reproduction with a single master mold in practical advantages.

2. EVALUATION OF GEAR ACCURACY BY TRANSMISSION ERROR MEASUREMENT

Transmission error of single flank engagement is defined as the deviation from the geometrically ideal rotation of a driven gear. When an input rotational speed is constant, transmission error can be regarded as the variation of output rotational motion. In the ideal engagement, we write as follows:

$$A_1 : A_2 = z_2 : z_1 \quad \text{or} \quad A_2 \cdot \frac{z_2}{z_1} - A_1 = 0 \tag{1}$$

where A_1 and A_2 are rotational angles of a driving gear (driver) and a driven gear (follower), and z_1 and z_2 are the number of teeth of a driver and a follower respectively. Transmission error (TE) is therefore defined by the following equation.

$$TE_p = A_2 \cdot \frac{z_2}{z_1} - A_1 \tag{2}$$

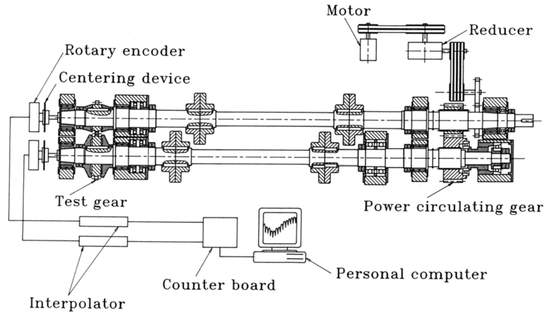


Fig.1: Typical illustration of transmission error measurement system

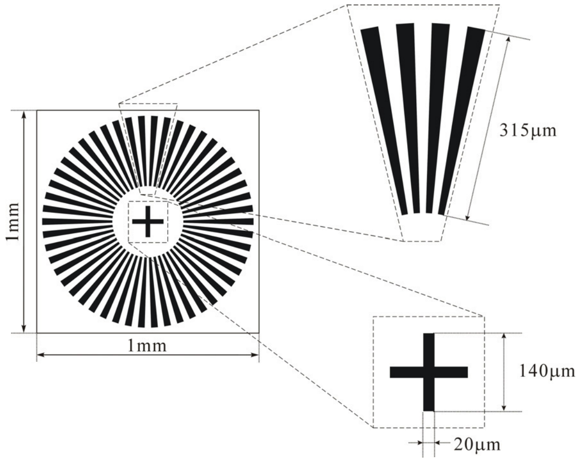


Fig.2: Example of designed grating disk pattern

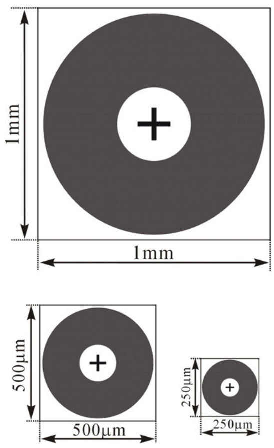


Fig.3: Designed grating disk patterns in different diameters

TE_p is transmission error based on a driver in units of rotational angle. Based on a follower, we can rewrite it in the different way:

$$TE_g = A_2 - A_1 \cdot \frac{z_1}{z_2} \tag{3}$$

In many cases, the representation of TE_p is normal. When we want to investigate transmission error in units of length along the line of action, we have the following equation for involute-profiled gears.

$$\begin{aligned} TE_d &= TE_p \cdot r_{b1} = TE_g \cdot r_{b2} \\ &= \left(A_2 \cdot \frac{z_2}{z_1} - A_1 \right) \cdot r_{b1} = \left(A_2 - A_1 \cdot \frac{z_1}{z_2} \right) \cdot r_{b2} \end{aligned} \tag{4}$$

where r_{b1} and r_{b2} are radii of base circle of a driver and a follower respectively. Because TE_d is the length along the common normal direction of engaging gear teeth, we can easily compare transmission error with the height value of tooth flank topography.

In any case, it is therefore necessary to detect rotational angles A_1 and A_2 of both driver and follower. The easiest way is to implement a pair of rotary encoders. For conventional-sized gears, a typical transmission error measuring system is like in Fig.1 [5].

The measuring system consists of a back-to-back type gear-testing machine in order to investigate under high-applied load of actual running conditions. A pair of optical rotary encoders is installed to the end of each shaft and they are connected through interpolating units to a personal computer. Sinusoidal waves from each rotary encoder are divided electrically and transformed into a series of pulses. The counter board detects the rotational angle of each shaft by counting those output pulses.

The target of measurement here is supposed to be a micro gear pair whose reference diameter is smaller than 1mm. For such a micro gear pair engagement, the center distance will be smaller than about 1mm. Therefore the diameter of a designed grating disk of a micro rotary encoder should be also smaller than the center distance. The smaller the grating disk diameter becomes, the wider the application for micro gear measurement extends. The authors here try to manufacture the grating disk whose diameter is smaller than 1mm.

3. DESIGN OF GRATING DISKS

A designed grating disk pattern is shown in Fig.2. All essential features are arranged within the field of 1 mm squared. The outer diameter is 950μm, and the inner diameter is 320μm. Each of the radial gratings has the same shape of the trapezoid, and its length is 315μm in the radial direction. At the center of the grating disk, the cross-shaped mark is drawn to be recognized easily. This center mark will be useful to adjust the eccentricity between the center of rotation and the center of the grating disk when the disk is mounted on a rotational shaft. The width of each radial grating depends on the number of gratings on a disk, which decide the resolution of the rotary encoder. That means it will be more difficult to manufacture the grating patterns as the disk diameter gets smaller. In the case of 10,000 gratings, the width at the inner end is only about 50 nm. In such a resolution grating disk, the line width becomes very narrow due to the tiny disk diameter.

Other grating disks which have smaller diameters than 1mm may be manufactured by keeping almost the same line width as that of the former design. Just a half and a quarter diameters were considered with the same radial grating patterns as Fig. 2 but with the different number of gratings. Designed patterns are illustrated in Fig. 3 comparing to that of the original size of 1mm in diameter. The grating pattern of 500μm in diameter has just the same line width as that of 1mm in diameter, because the diameter is just a half size and so is the number of gratings (5,000 gratings). Geometrically speaking, there is no difference between the grating line width of 1mm in diameter and that of 500μm in diameter, however the flow situation of a gas etchant is affected by not only the line width, but the line length and the groove depth in actual etching processes. The line length is shorter in 500μm diameter pattern than in 1mm one in this case, so it might be difficult to fabricate a small diameter grating pattern. The grating pattern of 250μm in diameter is the severest one among three sizes of the grating disks. The number of gratings is 3,000 and the line width at the inner end reaches 42nm.

To manufacture such a tiny radial grating pattern, the nanomanufacturing technique is essential. To achieve both the narrow width of the gratings and homogeneity of it, it is utilized here the combination of EB lithography and etching technique of silicon substrate as a process of a silicon master mold.

4. NANOMANUFACTURING METHOD FOR MASTER MOLDS

Figure 4 shows the illustration of the whole procedure of EB lithography and dry etching. Material substrate is silicon (Si), on which EB resist is directly pasted by spin coating. Hard mask is not necessary this time because the depth of etched grooves in the following etching process is specified to be shallow (about 30nm). The desired pattern is drawn by electron beam on the EB resist, and EB resist is exposed by electron beam energy. After development procedure, the exposed area is removed, and the desired pattern of EB resist is formed by the difference of solubility of exposed and unexposed resist parts. By use of the remained resist as a mask, Si substrate is etched, and finally, the EB resist is stripped by O_2 plasma ashing.

The workpiece wafer is 152mm (6 inches) in diameter and the thickness of Si substrate is about 500μm. The thickness of spin-coated EB resist (ZEP520A, ZEON corp.) is about 50nm. EB exposure was carried out using a high-resolution electron beam lithography system. The system is based on an electron gun as exposure system (JBX-9300FS, JOEL Ltd.). The EB resist of the black drawn area in Fig.2 was exposed. Development after EB exposure was carried out by use of the developing solution (ZED-N50, ZEON corp.) with a rotary spray, and developing time was about 60s. After development, a rinse procedure was carried out for about 60s by use of the rinse agent (ZMD-B).

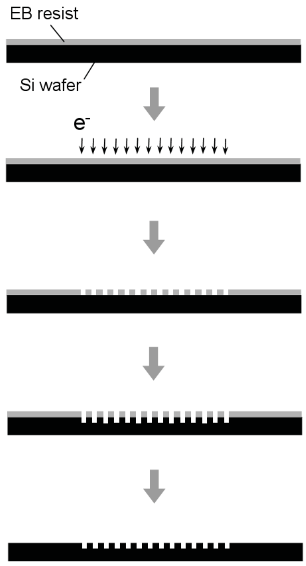


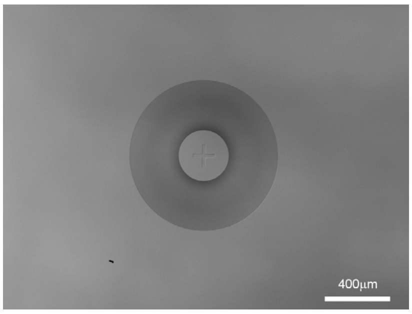
Fig.4: Procedure of EB exposure and dry etching process for a master mold

The dry etching was carried out using a dry etcher with a reactive ion etching (RIE) by utilizing inductive coupled plasma (ICP). In the RIE process, the hydrogen bromide (HBr) gas was used in etching Si substrate and the depth of etched grooves was intended to be about 30nm.

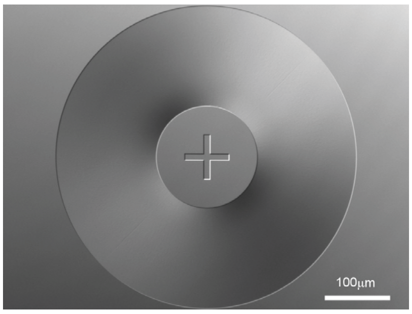
5. RESULTS IN THE MASTER MOLD PROCESS

The whole etched images of the radial patterns of 1mm, 500μm and 250μm in diameter were captured by the confocal laser scanning microscope (CLSM) (LEXT OLS3500, Olympus corp.) and are shown in Fig.5. The whole shapes of grating disk patterns seem to be successfully etched, but any radial gratings cannot be seen due to the limitation of low resolution of CLSM. Therefore, the scanning electron microscope (SEM) was used to observe the details.

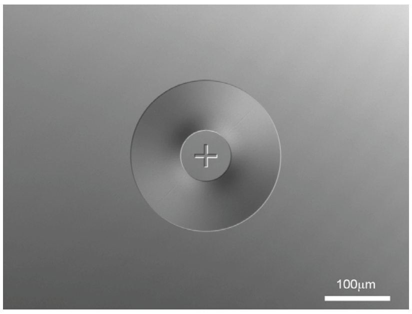
Figure 6 shows the SEM image of the outer end of the part of radial gratings and that of the inner end of those of 1mm in diameter. The etched line width at the outer end is about 150nm and that at the inner end is about 50nm as intended. It has been manufactured also almost homogeneously with enough pitch accuracy. From those results, a grating disk up to 50 nm line widths can be manufactured successfully and accurately. The accuracy of these repeated grating



(a) 1mm in diameter



(b) 500μm in diameter

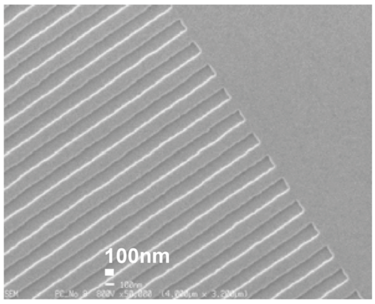


(c) 250μm in diameter

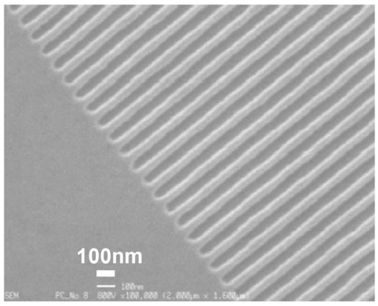
Fig.5: CLSM images of the whole grating disks

patterns affects the accuracy of the rotary encoder directly.

SEM images in the case of the radial patterns of 250μm in diameter are shown in Fig.7. The etched line width at the outer end is about 125nm as intended, but that at the inner end is obviously a little wider than the designed one of 42nm. The reason is that the amount of exposure might be a little large. Since the etched Si substrate is used as a Si master mold in the following imprint process, even such narrow grooves must be manufactured securely without incomplete etching. The indispensable property for the grating disk is to have accurate line widths with homogeneous pitches at even intervals. The deviation range of the detected pitches from magnified SEM images is within plus or minus 5nm from the theoretical pitches in all cases of the line width. The result in this case is therefore regarded to be suitable for the practical manufacturing on the side of prudence.

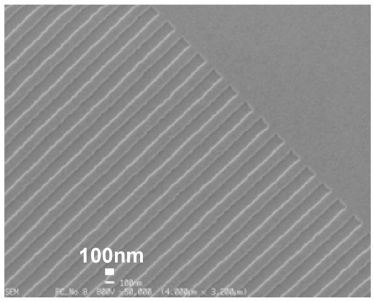


(a) At the outer end

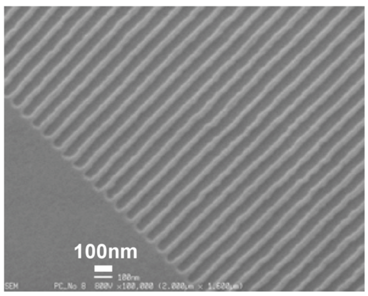


(b) At the inner end

Fig.6: SEM images of 10,000 gratings of 1mm in diameter



(a) At the outer end



(b) At the inner end

Fig.7: SEM images of 3,000 gratings of 250μm in diameter

6. NANOIMPRINTING TECHNIQUE FOR A REPLICATION METHOD

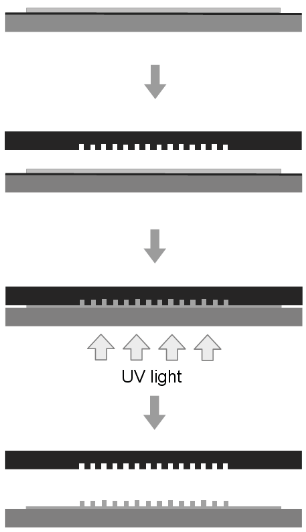


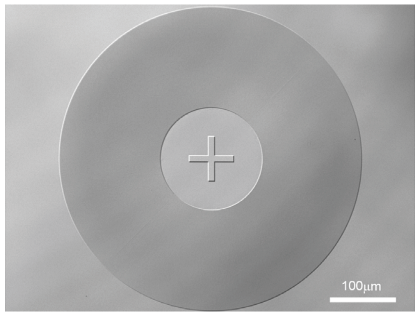
Fig.8: Procedure of photo-nanoimprint method

Once the Si substrate is manufactured successfully, it should be used as a master mold of replication methods suitable for mass production. The most interesting method is nanoimprinting technique. Figure 8 shows the illustration of the whole procedure of photo-nanoimprint method. Material substrate is soda-lime glass, of which surface is given by primer treatment with polyester agent. Acrylic ultraviolet (UV) curable resin is dropped on the treated surface with even thickness. The glass substrate is mounted on the glass stage of a nanoimprint apparatus and a Si master mold is attached on the press plate. The master mold is pressed against the UV curable resin at the specified pressure, and UV light is illuminated from backside. After curing the resin, the master mold is demolded manually from the substrate.

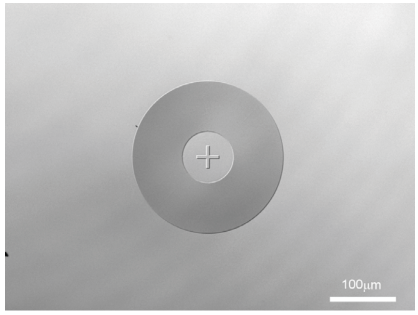
The glass substrate is 150mm squared and the thickness of the substrate is about 1.1mm. The thickness of primer layer of polyester agent is about 1μm. The nanoimprint apparatus is a simplified desktop type by use of an air cylinder for pressing mechanism. Contact pressure of the mold against the UV curable resin was set to be about 0.3MPa, and UV light source was a high-pressure mercury lamp with illumination intensity of 500mJ/cm^2.

7. RESULTS IN THE NANOIMPRINT PROCESS

Figure 9 shows the whole imprinted images of the radial patterns of 500μm and 250μm in diameter captured by CLSM. The whole shapes of a grating disk patterns seem to be successfully imprinted. Since it is difficult to observe tiny patterns of resin materials by SEM, the surface is measured by atomic force microscope (AFM) in detail. The measured AFM images of the outer end are shown in Fig. 10.

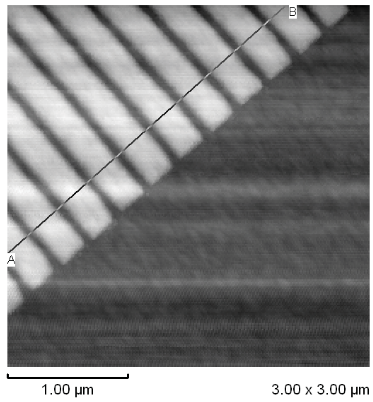


(a) 500μm in diameter

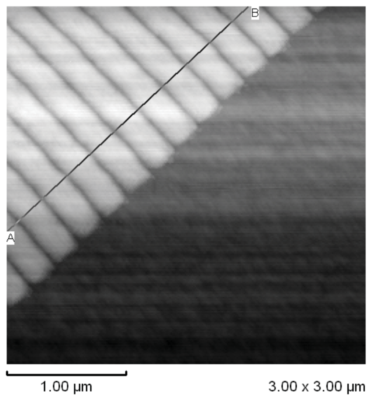


(b) 250μm in diameter

Fig.9: CLSM images of the whole imprinted grating disks



(a) 500μm in diameter



(b) 250μm in diameter

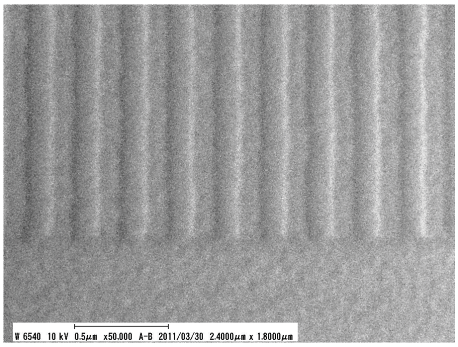
Fig.10: AFM images of the outer end of imprinted gratings

The results show the detected pitches are almost the same as those of the master molds. Basically, the pitch is accurately replicated in nanoimprint process if there is no filling defect of the UV curable resin. From the fact, it is predicted that each line width is homogeneous and arranged at even intervals as that of the master mold is. The AFM images however are difficult to be handled because those images are essentially time-series data during measurement and there are nonnegligible disturbed fluctuations from measuring circumference conditions. Unfortunately, an ordinary SEM is not appropriate to observe the resin surface, either, so we used a highly-functional Electron Probe Surface Roughness Analyzer, ERA-SEM (ERA-8900, ELIONIX Inc.) which has 4ch detectors of secondary electrons enabling to capture both the conventional SEM images and three-dimensional roughness analysis to verify the homogeneity of the replicated lines. Since it takes quite long time to analyze whole grating patterns even by the ERA-SEM, the outer and inner ends at every 90° were observed in the area of 2.4μm×1.8μm.

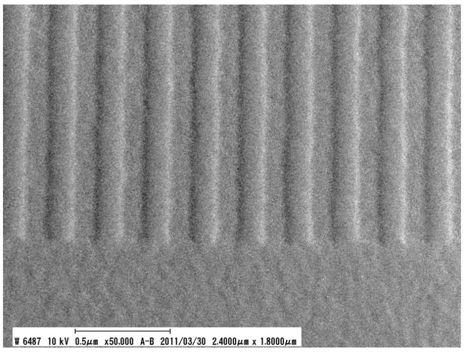
An example of concave-convex enhanced ERA-SEM images of the imprinted radial gratings of 250μm in diameter is shown in Fig.11. The deviation range of the detected pitches from ERA-SEM images is within plus or minus 5nm from the theoretical pitches at every 90° of the outer and inner ends. From those results, a grating disk of which diameter is 250μm can be manufactured successfully also by the nanoimprint process almost homogeneously with enough pitch accuracy.

8. DISCUSSIONS TO REALIZE A MICRO ROTARY ENCODER

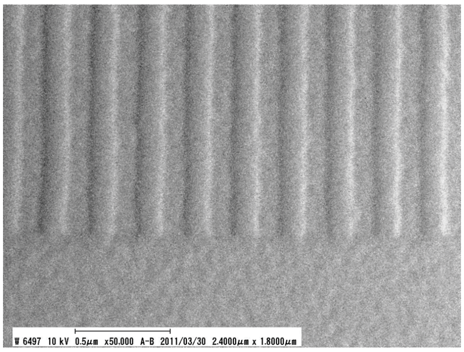
The signal detection is the next important issue with the manufactured grating disks. Contact methods and non-contact detection will be considered. The first approach is to use a contact type stylus with controlled tip radius. An AFM stylus with dynamic mode will be useful in this case. If the grating disk rotates while the AFM stylus taps the surface at the same position without scanning motion, the detected height variation will be regarded as the output signal of a rotational angle of the grating disk. To achieve high resolution, it is necessary that all the detected local peaks should be the smooth mountain shape and each height changes gradually according to the position. The shape control of the local peak might be achieved by etching process in the master mold grooving. Since an AFM stylus vibrates at high resonance frequency (up to 300kHz) in dynamic mode measurement, signal detection can be realized under the rotational frequency within allowable limit. If multi-probing system with multi-AMF styli is adopted, the opposite reading cancels out the influence of disk eccentricity, and self-calibration will be also possible.



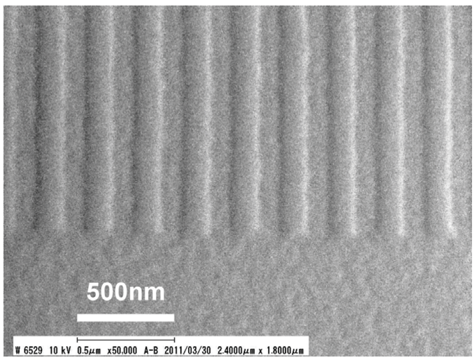
(a) At the angular position of 0°



(b) At the angular position of 90°



(c) At the angular position of 180°



(d) At the angular position of 270°

Fig.11: Enhanced ERA-SEM images of the outer end of imprinted gratings of 250μm in diameter

The second approach is non-contact detection. Normal light detection cannot be utilized because of the limitation of a light wavelength. The authors believe one of the effective detections will be the use of the evanescent light. If the sinusoidal output signal is obtained, the conventional signal processing is applicable to improve the resolution.

Although there are many issues to be overcome to realize a high precision micro rotary encoder, rotary encoders have great advantages such as robustness against temperature changes, possible error compensation, and applicable self-calibration technique.

9. CONCLUSIONS

For the evaluation of micro gear accuracy, different sized grating disks for micro rotary encoders suitable for transmission error measurement were designed and manufactured with EB-lithography and nanoimprinting techniques aiming for practical application of micro gear measurement. The grating patterns, of which line width is up to 50 nm, were successfully manufactured homogeneously and accurately on the Si substrate. The nanoimprint process was also achieved successfully with the Si master mold. The result shows that it is possible to manufacture a grating disk of which diameter is smaller than 1mm and the number of gratings is at least 10,000 as mass production. The smaller grating disk than 1mm in diameter was also manufactured to the diameter of 250μm.

The signal detection is the next important issue. Since traceability for angle is already established, the calibration procedure of the micro rotary encoder is also another significant issue.

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