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REGULAR PAPER

Manufacture of microscale random pattern using indentation machining technology

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Abstract

The display industries recently demand new microscale dot-type patterns for thinner and brighter displays with high energy efficiency, which are randomly distributed with irregular separation distances and have uniform optical characteristics. We developed a new program to generate the coordinates of the controlled microscale random patterns considering their diameter and the distance to the nearest pattern for preventing overlap of each pattern. Then the microscale random patterns were machined on a metal mold using the indentation machining which is a simple and low-cost machining method. We decreased the total machining time by the optimization of machining order of the random patterns. The coordinates, the diameter and the fill-factor of the machined patterns by the indentation machining were much consistent to the designed values. The controlled microscale random patterns had uniform optical characteristics over all areas of the manufactured optical film. Moreover, if optical films have the same diameters and fill-factor, they showed the same optical characteristics even they have totally different coordinates of random microscale patterns. This technology is expected to reduce the number of the optical films and the light sources in the display, which can save much energies.

Keywords Indentation machining · Microscale random pattern · Fill-factor · Optical characteristics

1 Introduction

Recently in the display industry, films with specific micropatterns have been manufactured and inserted into products to diffuse the light source. Film patterning can reduce the number of light sources in the display without decreasing the uniformity of luminance over the entire area [1–5]. Conventional micropatterns consist of continuous and linear patterns, such as a prism pattern [6, 7] a lenticular pattern, [8] and others [9]. These patterns are used for diffusing or concentrating lights. As the displays are thinner, the diffusing of lights becomes more important because the lights should be distributed evenly on all surfaces of the display. In order to distribute the light evenly, the sufficient distance between the light sources and the surface of the display is needed to spread the lights. It is more difficult to ensure the sufficient distance in case of the thinner display. However, the conventional micropatterns can be recognized by the eyes of customers in much thin displays, and this phenomenon is regarded as a defect by the display industry. A major contributor to recognition of the micropattern is the regular pitch of conventional linear patterns. In order to resolve this problem, randomly distributed microscale dot-type patterns with irregular separation distances (non-constant pitch) can be used [10–12]. However, films with completely randomly distributed microscale patterns have large variations of optical characteristics, which is not appropriate for display technologies. Therefore, development of a new method to design and to manufacture microscale random patterns with uniform optical characteristics is necessary.

The microscale random patterns generated by simple random functions using commercial programs with no controlled parameters can overlap each other. This issue can be

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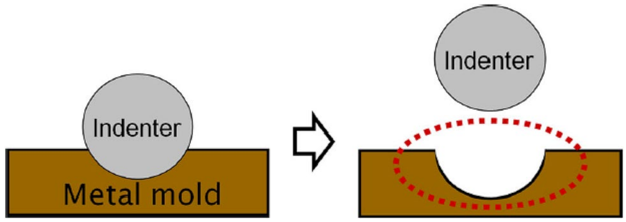


Fig. 1 A novel indentation machining technology combining a dynamic indentation method and mechanical machining of a metal mold [18]

addressed by considering the diameter and the distance of microscale random patterns to prevent overlap. In addition, the fill-factor, defined as the area covered by the microscale random patterns over a whole area, should be controlled to maintain uniform optical characteristics. In this study, we develop a new method for designating the coordinates of microscale random patterns with the design considerations of diameter and fill-factor. Conventionally, microscale patterns are manufactured by wet-etching [3, 13–15] or laser machining [15–17]. Though wet-etching enables fast manufacturing of microscale patterns, it is hard to control the coordinates of microscale random patterns accurately with this method. Laser machining can control the coordinates accurately and create long patterns with high aspect ratio, however, it is hard to change the vertical shape of the microscale patterns created with this method, which can significantly affect the film's optical characteristics. In this study, we propose to address these challenges with the use of indentation machining. Indentation machining can control the coordinates' microscale random patterns accurately and also enables to change the vertical shapes in the pattern (e.g., sphere, pyramid, rectangle, etc.). Moreover, the operating principle of indentation machining is much simpler than

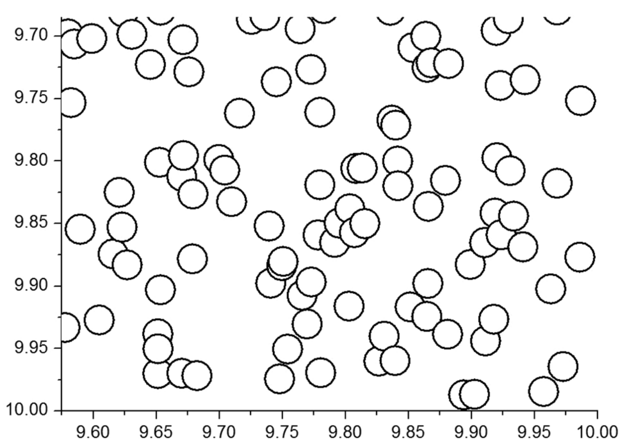


Fig. 2 Coordinates of uncontrolled random pattern with diameter of 25 μm and a fill-factor of 40% without consideration of the distance between each pattern

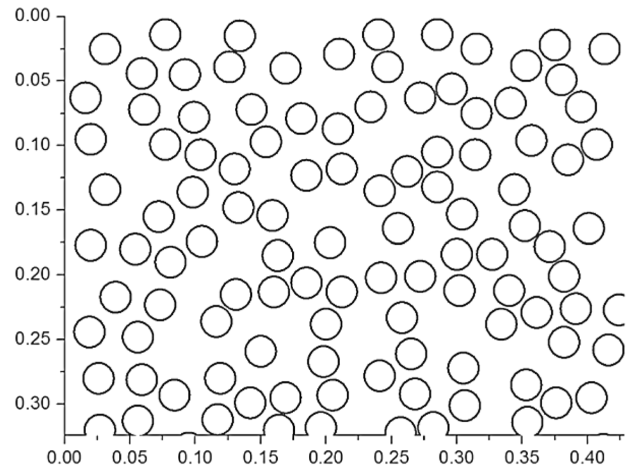


Fig. 3 Coordinates of controlled random pattern with diameter of 25 μm and a fill-factor of 40%, generated by the newly developed program in this study

conventional manufacturing methods because it is based on an indentation hardness test, which is the simplest mechanical testing method. Therefore, we studied the manufacture

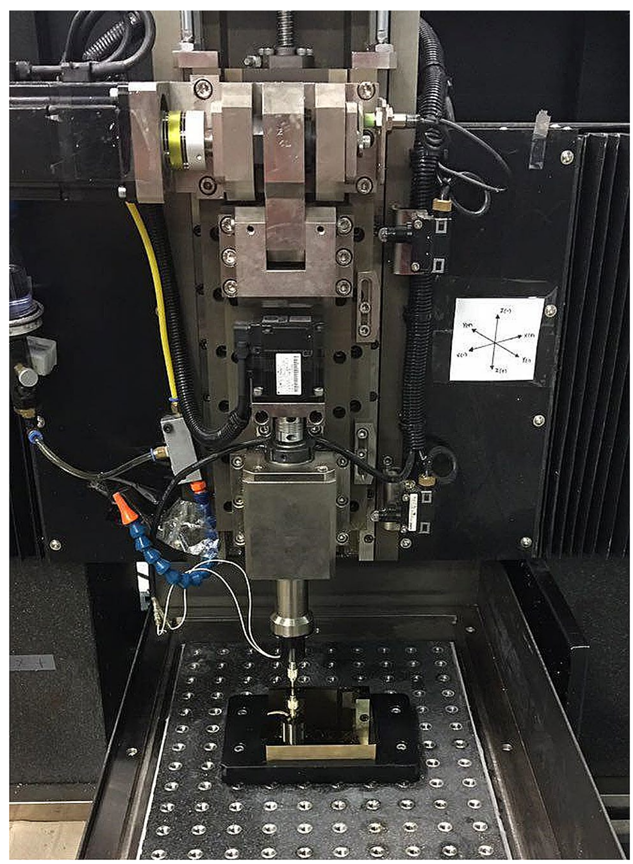


Fig. 4 A dynamic indentation machining system used for precise planing and machining of microscale random patterns

of microscale random patterns designed by a new method using indentation machining.

2 Indentation machining

Indentation hardness test is done simply by pressing a material with a specific indenter and removing the indenter from the material. The shapes and the sizes of residual indentations are dependent on the shapes of the indenter and the applied force, respectively. This same mechanism can be applied to purposely use the indenter to create a predefined pattern. The indenter and the residual indentation are regarded as a machine tool and a machined pattern, respectively in case of the indentation machining. This method allows for control of the position of the patterns, and the pattern can be manufactured in random or regular microscale patterns. In addition, the indentation machining can be applied to mass production through the formation of microscale patterns on a metallic mold, as shown in Fig. 1 [18]. This method neither requires an expensive mask nor post-processing for chemical removal, which keeps indentation machining simple and cheap [19]. Using the machined metallic mold, optical films can be manufactured by a molding process.

We have previously demonstrated the usefulness of indentation machining for the manufacture microscale patterns [18], and summarize the results briefly in this chapter. Inhomogeneous plastic deformation called pile-up [20–24] of a brass mold was reduced by annealing for 12 h at 575 °C and furnace cooling, which improved the quality of machined pattern significantly. A new dynamic indentation machining system was developed to decrease the machining time of microscale patterns with a maximum speed of 10 Hz. The diameter of the microscale patterns could be tuned from 10 µm to a few mm by changing the input current or input voltage to the actuator. The previous studies [18, 24] focused on developing the indentation machining technology by minimizing the inhomogeneous plastic deformation and used a large diameter of 1.2 mm with a regular pitch. Therefore, to improve upon previous results whose purpose was to develop a new machining technology, we focused on manufacturing a precise metal mold with microscale patterns with random pitches using the indentation machining, and optical films possibly applicable for displays in this study.

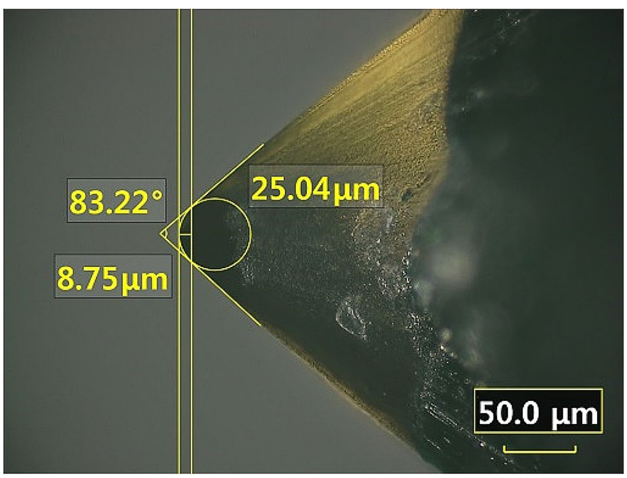


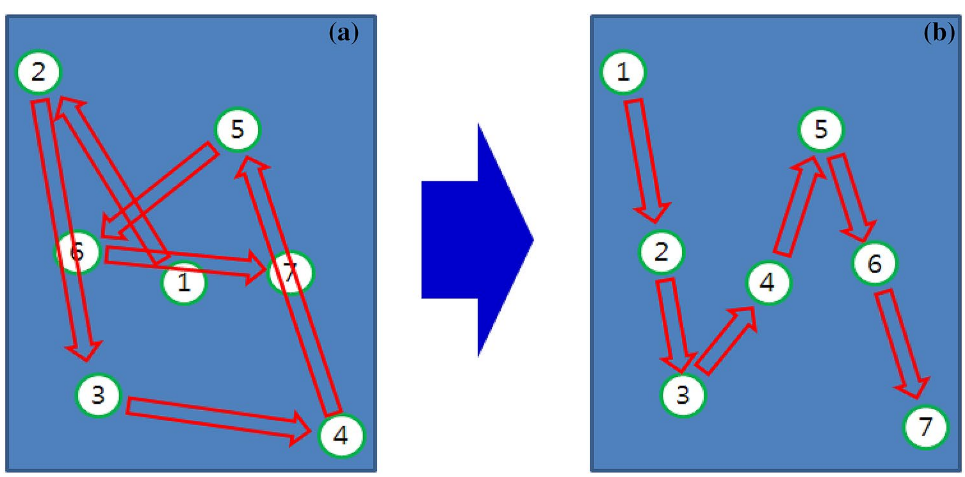
Fig. 5 A machine tool with radius of 25 µm for indentation machining

3 Manufacturing of microscale random patterns

3.1 Design of microscale random patterns

As mentioned above, if the microscale random patterns are generated by simple random functions using commercial programs with no controlled variation, they can

Fig. 6 Schematics of the orders of indentation machining **a** without and **b** with rearrangement of the machining order of the random patterns. Rearrangement reduces machining time



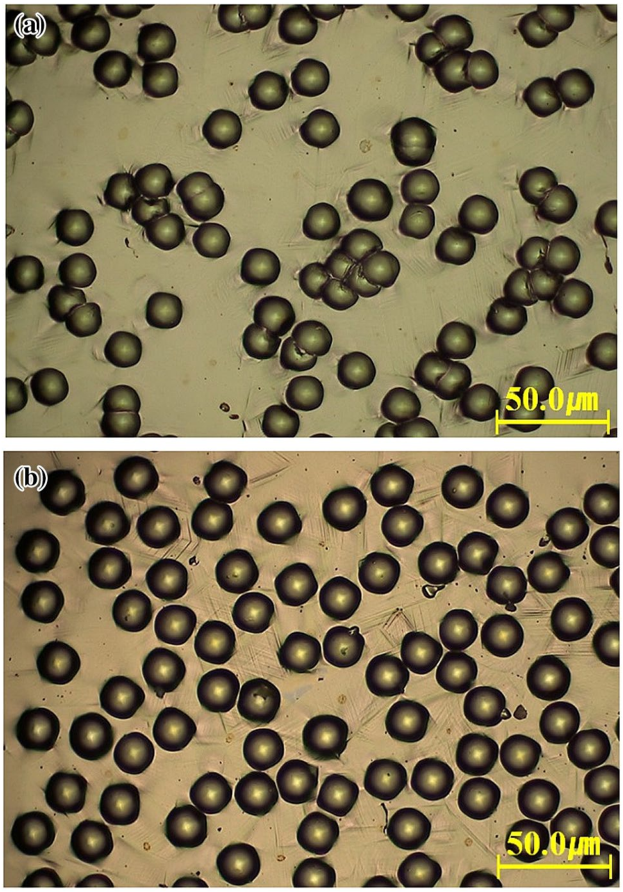


Fig. 7 Machining results of **a** uncontrolled random patterns and **b** controlled random patterns (diameter of 25 μm and a fill-factor of 40%)

overlap each other. In order to prevent the overlap, the distance from one pattern to the closest pattern should be larger than the diameter of the microscale random patterns. Moreover, the fill-factor should be controlled for maintaining uniform optical characteristics across the film. We set the diameter and the fill-factor to be 25 μm and 40%, respectively, based on the demands of an industrial company. If the entire pattern area is 10 mm × 10 mm with the target diameter and fill-factor, the total number of microscale random patterns is about 80,000. Since it is impossible to generate the coordinates and to calculate the whole distances of such a large number of microscale random patterns without a help of a computer, we developed a program using MATLAB for generating the coordinates of each microscale random pattern. A controlled random pattern was generated by the program that controlled the diameter and the fill-factor of the microscale random patterns to produce no overlap. Another program was written to generate an uncontrolled random pattern of coordinates without considering the distance between microscale random patterns for comparison. Figures 2 and 3 show parts of the uncontrolled random patterns and the controlled random patterns generated by each program. There is most patterns in Fig. 3 overlapped each other as expected; however, no overlap in Fig. 3. The overlap decreased the covered area of the microscale random patterns, resulting in a real fill-factor that is lower than the target fill-factor. Moreover, the shapes of some microscale random pattern were not spheres, but dumbbells. Therefore, the distance between each microscale random pattern should be considered when generating the coordinates of microscale random patterns.

3.2 Machining and manufacturing of microscale random patterns

Metallic molds were manufactured based on the two sets of generated coordinates for the designed microscale random patterns using the dynamic indentation machining system in Fig. 4. The system has a resolution of 3 nm on three axes and the maximum manufacturing area of 350 mm × 350 mm. The system enabled precise planing process by simply switching the system's machine tools, thus, it was possible to manufacture the microscale random patterns by indentation machining immediately after ultra-fine planing. A mirror-surface on the metallic mold was machined by ultra-fine planing before indentation machining in order to machine the microscale random patterns with low roughness. The metallic mold was created with brass and annealed for 12 h at 575 °C. This was followed by furnace cooling to reduce pile-up as reported previously [18]. The machine tool for the indentation machining was a conical tool with a 25 μm radius, as shown in Fig. 5.

When generating the coordinates of random patterns, the order of the generated coordinates is also random. If the random pattern is machined following the order of generation, the machine tool should move longer distance than it would for regular patterns, as shown in Fig. 6a, which increases machining time and costs. Hence, the order of indentation machining was rearranged to reduce the machining time as shown in Fig. 6b. The generated coordinates were sorted in ascending order along the *x*-axis. Then, we sorted them along the *y*-axis in ascending order and then in descending order as a sequence. After the rearrangement of the machining orders, the machining time was decreased to 40% of the time required with no rearrangement.

Figure 7 shows the machining results of microscale random patterns on metallic molds. As discussed in Chap. 3.1, the uncontrolled random pattern included a lot of overlap, whereas almost all of the controlled random patterns were isolated. There was very little pile-up around the two types random patterns, which might be due to the annealing and furnace cooling processes undertaken before machining as verified in previous research. To confirm the consistency

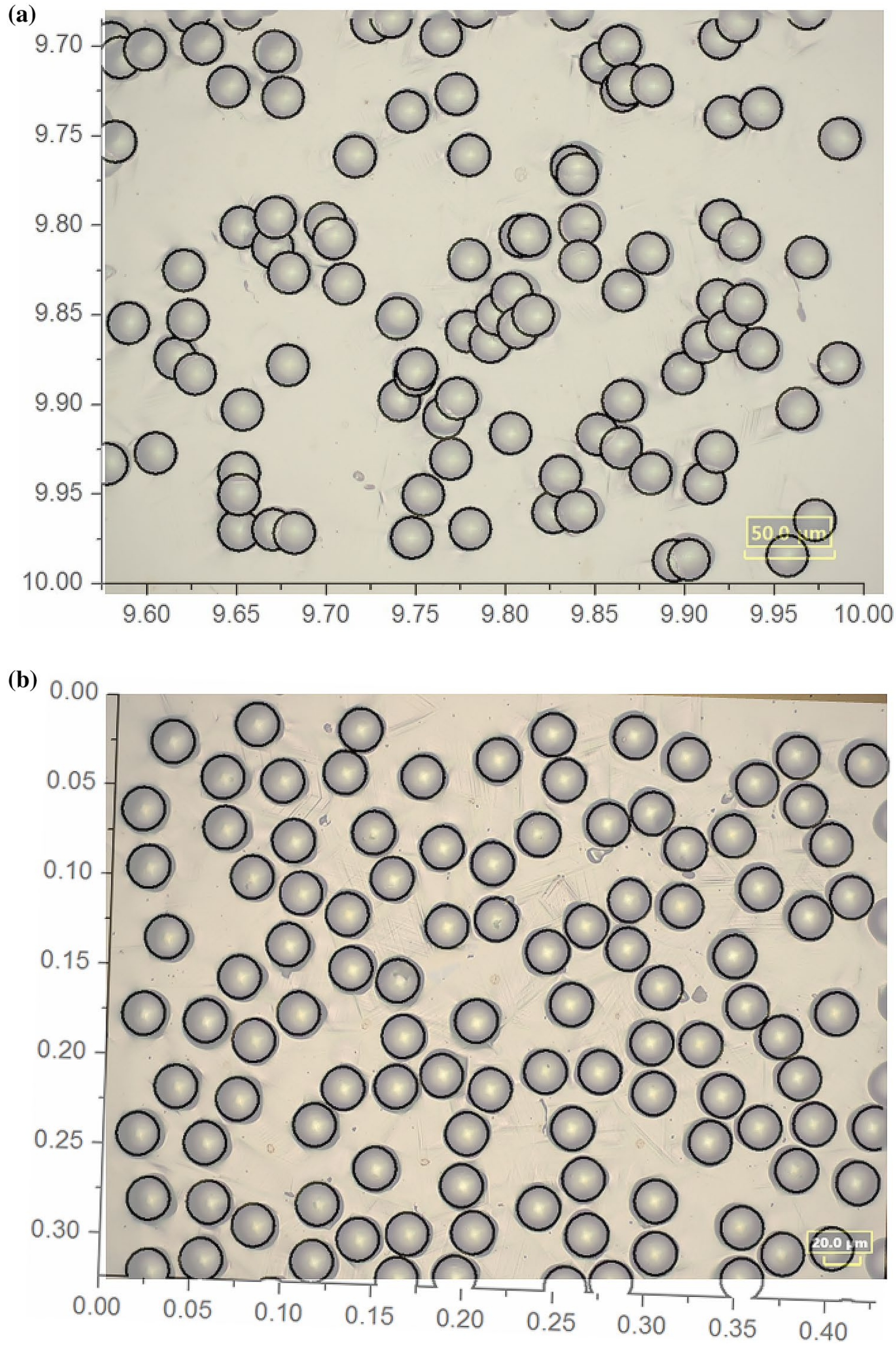


Fig. 8 Comparison of design results and machined molds of **a** uncontrolled random patterns and **b** controlled random patterns

between the design of the microscale random patterns and the machined microscale random patterns on a metallic mold, the design results of Figs. 2 and 3 were overlaid on microscopic images of the machined mold, as shown in Fig. 8. The diameters and the coordinates were almost in perfect agreement in both the uncontrolled and controlled random patterns. These results meant that the microscale random patterns were machined with accurate positions and size by indentation machining, regardless of the pattern spacing.

As previously mentioned, the two types of random patterns shown in Fig. 8 were designed and machined with a target fill-factor of 40% and target diameter of 25 µm. In order to determine whether the fill-factors of the two machined molds were consistent with the target fill-factor, the diameters of 20 random patterns of five sections at each mold were

Table 1 Comparison of target and measured diameters and fill-factors of uncontrolled random patterns and controlled random patterns

	Designed diameter (μm)	Measured diameter (μm)	Designed fill-factor (%)	Measured fill-factor (%)	Standard deviation of fill-factor (%)
Controlled random pattern	25	25.48	40	41.23	1.32
Uncontrolled random pattern	25	24.54	40	30.65	4.62

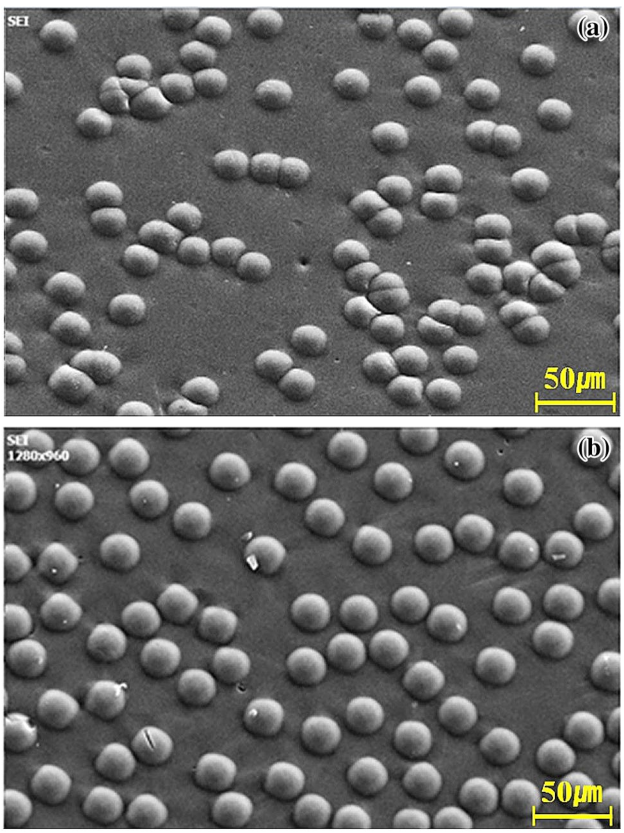


Fig. 9 SEM images of the manufactured films with **a** uncontrolled random patterns and **b** controlled random patterns

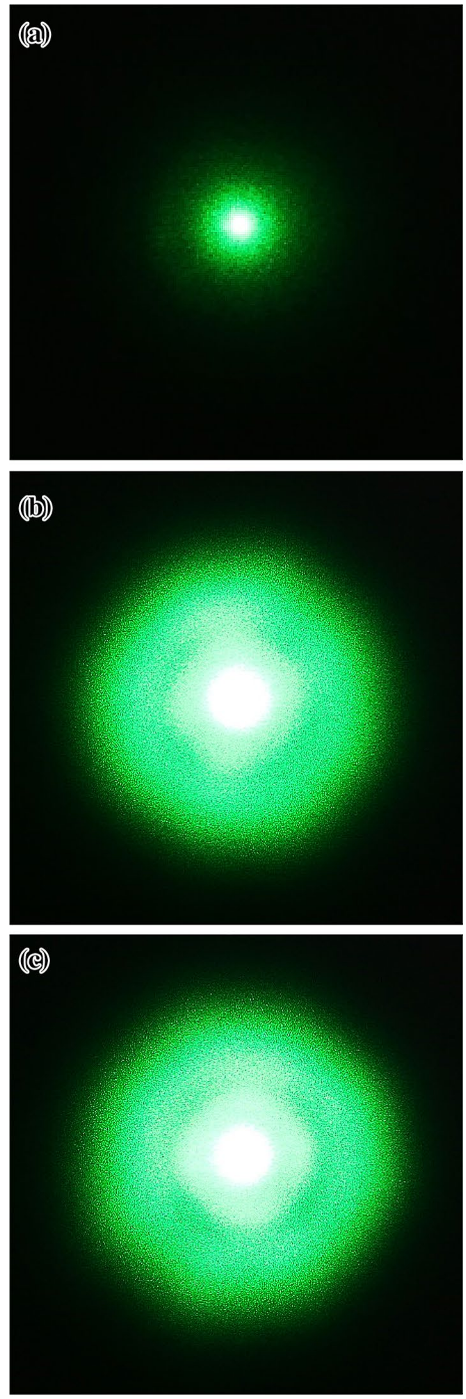


Fig. 10 The shapes of final spots of laser light that had passed through optical films with **a** no pattern, **b** controlled random pattern Sect. 1 and **c** controlled random pattern at Sect. 2

measured and used to calculate the measured diameter. The fill-factor was also obtained by measuring the five sections of each mold using an image analyzer. The image analyzer could measure the covered area of the random patterns by analyzing color of photos. The measured diameters and the measured fill-factors are present in Table 1. The average diameters of two types of random patterns were similar to the target diameter with error of less than 1 μm. However, the measured fill-factor of the uncontrolled random patterns was about 10% (normalized error was about 25%) lower than

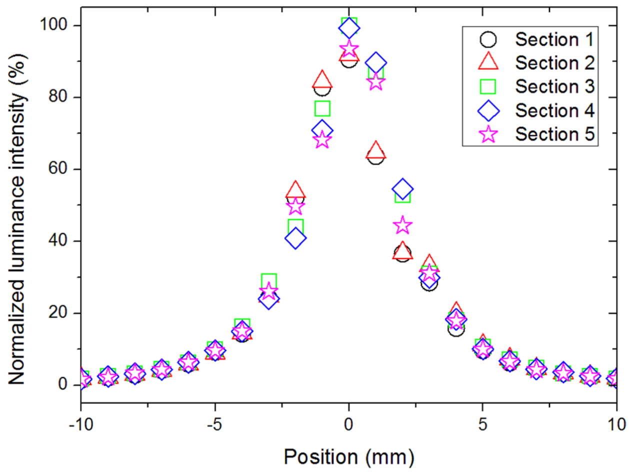


Fig. 11 Comparison of the distributions of luminance of final spots measured at five different sections of one optical film having controlled random patterns

the target fill-factor, even though the measured value of the controlled random patterns were similar to the target value. Moreover, the standard deviation of the measured fill-factor in five sections of the uncontrolled random patterns was more than three and half times that of the value for the controlled random patterns. These errors and non-uniformities occurred due to the uncontrolled overlap of each random pattern. The measured fill-factor was lower than the target value because the overlap decreased the covered area of the random patterns. The non-uniformity increased because the number of overlapped random patterns was random. Therefore, the distance between each random pattern should be considered when designing the coordinates of microscale random patterns for preventing overlap of each random pattern and for maintaining the fill-factor.

Ultraviolet light-cured resin and thin transparent polymer films were used to manufacture optical films from the two types of the metallic molds of microscale random patterns. The resin was covered on the two machined metal molds, and the machined microscale random patterns were transferred onto transparent films. The diameters of the random patterns in Fig. 9 were about 25 µm and there was no pile-up around the patterns, which means the machined random patterns were well transferred. The film from the uncontrolled random patterns contained many overlapped patterns, in agreement with the machined metal mold (Fig. 7a), while the film from the controlled random patterns did not contain overlaps (Fig. 7b). Finally, optical films with controlled random patterns were successively manufactured.

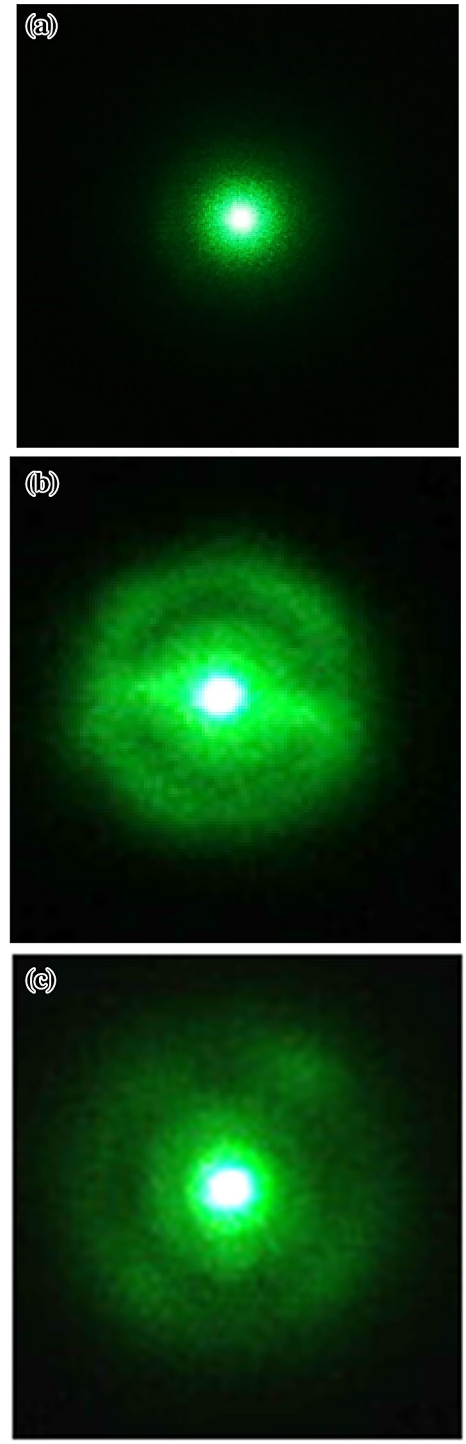


Fig. 12 The shapes of final spots of laser light that has passed through optical films with **a** no pattern, **b** uncontrolled random pattern at Sect. 1 and **c** uncontrolled random pattern at Sect. 2

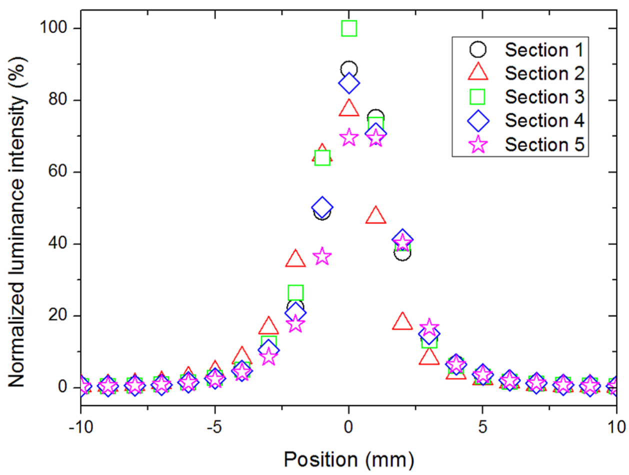


Fig. 13 Comparison of the distributions of luminance of final spots measured at five different sections of one optical film with uncontrolled random patterns

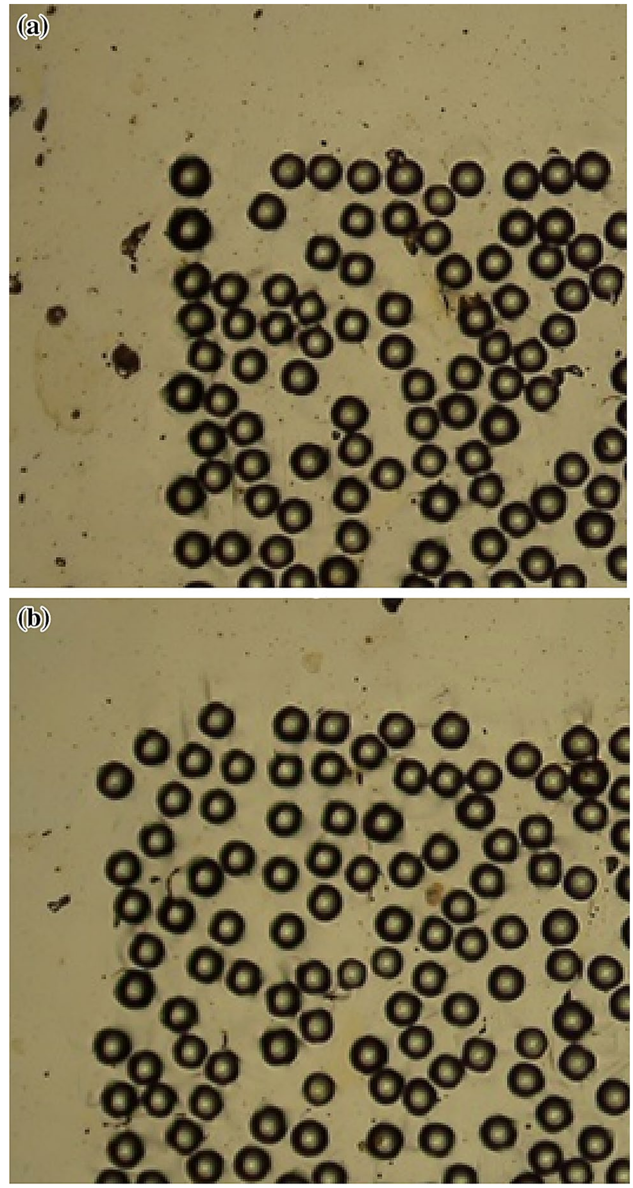


Fig. 14 Comparison of machining results of **a** conventional coordinates and **b** new coordinates with a diameter of 25 μm and a fill-factor of 40%

4 Optical characterization of controlled random patterns and uncontrolled random patterns

The optical characteristics of the controlled random patterns and the uncontrolled random patterns were evaluated using a green laser and a two-dimensional luminance measurement system. The laser passed through the manufactured optical film, and was diffused by the transferred microscale random patterns. The spot size of the laser from its source in this study was 2 mm, and final spot sizes of the passed laser were compared. Since laser light is collimated, a final spot size that is larger than the original spot size indicates that the manufactured film has excellent light-diffusing functionality. The distribution of luminance was also measured at the center line of the spot using a two-dimensional luminance measurement system. The spot size and the distribution were measured at five different sections of each film in order to verify no variation of optical characteristics over the entire area of the optical film. An optical film with no microscale pattern was also manufactured using the same ultraviolet light-cured resin and the same transparent polymer film as a reference.

First, we compared the shapes of the spots of laser light that had passed through the optical films with no pattern or the controlled random patterns. The brightest area of resulting from the film with no pattern was the same as the original laser spot (Fig. 10a). The laser diffused a little as it passed through the film due to the inherent optical characteristics of the transparent polymer film and the flat resin. However, the final spots created by the optical films with the controlled random patterns were much larger than the original spot. This meant that the microscale random patterns can diffuse light very effectively. Moreover, the shapes of the spots measured at two different sections, as shown in Fig. 10b, c, were similar to each other. The distribution of luminance of the final spots measured at five different sections of one optical film with controlled random patterns had less than 10% variation and overlapped well (Fig. 11), which means that the optical film with controlled random patterns had uniform optical characteristics over all areas. The five different sections were selected on the two diagonal lines. The diagonal lines were divided into four parts evenly, and three points were obtained on each diagonal line. The middle

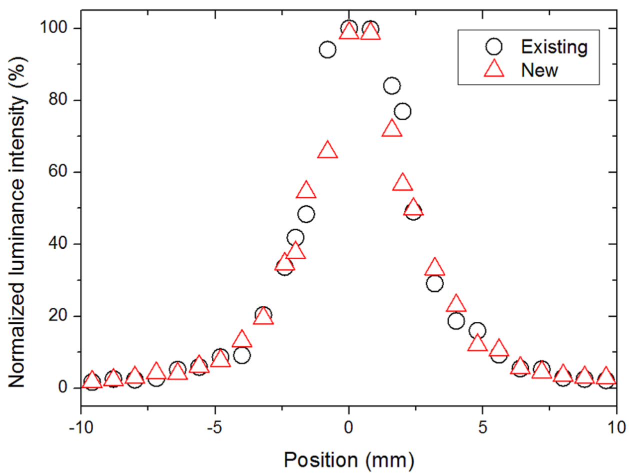


Fig. 15 Comparison of two distributions of luminance of final spots conventional coordinates and new coordinates with the same diameter of 25 μm and same fill-factor of 40%

points of the two lines were same. We used the five points as the centers of the five different sections.

In contrast, the final spots of the optical films having the uncontrolled random patterns in Fig. 12b, c were narrower than the final spots in Fig. 10. Moreover, the shapes measured in Sects. 1 and 2 were significantly different. The distributions of luminance from the uncontrolled random patterns (Fig. 13) had about 30% variation and did not overlap. This meant that the optical characteristics varied from section to section, as indicated by the large standard deviation in Table 1. Therefore, uncontrolled random patterns would be difficult to apply to industrial applications.

We assumed that optical films of controlled random patterns would have similar optical characteristics if they had the same fill-factor in this study. The coordinates of each microscale random pattern with a diameter of 25 μm and the fill-factor of 40% were newly generated by the developed program. A new metal mold was machined by the indentation machining technology according to the newly generated coordinates of the controlled random patterns. As shown in Fig. 14, two kinds of the controlled random patterns had entirely different distributions. The optical film of the controlled random patterns was manufactured by the same process as described in Chap. 3, and its optical characteristics were measured by the same method as described in Chap. 4. The two distributions of luminance of final spots in Fig. 15 had less than 5% variations. Therefore, it was verified that microscale random patterns having controlled diameter and fill-factor had the similar optical characteristics and could be applied to industrial fields.

5 Conclusions

We developed a new program to generate coordinates of microscale random patterns with controlled diameter and fill-factor, machined a metal mold using indentation machining technology, manufactured optical films using the machined mold and verified their optical characteristics. The details are described below.

(1) When generating the coordinates of random micro scale patterns, the distance between a pattern and the nearest pattern should be considered in order to prevent pattern overlap and to obtain an accurate fill-factor.
(2) Indentation machining technology can be applied to machine the designed microscale random pattern on a metal mold. The machined controlled random patterns had much similar coordinates, diameters and fill-factor to the designed values.
(3) The optimization of machining order of the random patterns can reduce the total indentation machining time significantly.
(4) The optical film can be manufactured easily by a molding process using ultraviolet light-cured resin, a thin transparent polymer film and the machined metal mold. This film can diffuse light effectively and has uniform optical characteristics over the area of controlled random patterns.
(5) This technology is expected to reduce the number of the optical films and the light sources in the display maintaining similar brightness to conventional displays without more energies.

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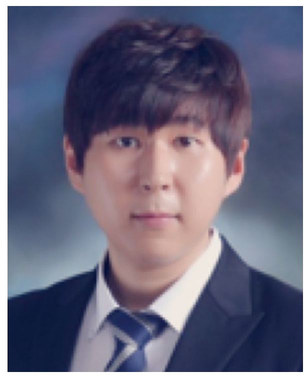

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