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Fabrication of Polymer Light Guide Plate (LGP) using Direct CO_2 Laser Structuring

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ABSTRACT

Light guide plate (LGP) is an integral component that help distribute illumination from the light source in a variety of applications. Therefore, the design and quality of the microstructure pattern in LGP play a significant role in achieving high luminous efficiency and light uniformity. This study investigates the relationship between laser power and laser scanning speed to the formation of micro-dots by using CO_2 direct laser structuring on PMMA. Furthermore, the effect of different micro-dots pitch to the luminance was also evaluated using the luminance meter. Our finding shows that increase of laser power and decrease of laser scanning speed resulted in larger micro-dots diameter and deeper micro-dots. The results also showed that the smaller the pitch, the higher the luminance reading. Overall, the low-cost CO_2 direct laser structuring demonstrated in the study able to produce consistent micro-dots pattern diameter and height which is suitable for fabrication of LGP in the mass production.

Keywords:
CO_2 laser; light guide plate; PMMA; micro-dots; luminance; microstructures

1. Introduction

The demand of small and compact devices has become increasingly important in various sectors including photonics [1,2], biosensors [3,4], biomedical [5] and optics [6]. Usually, these small devices require the production of micro and nano-scale patterns with different shapes and geometry. For instance, microfluidic devices with micro to nanopattern structures had been used to maximize the sensitivity in detecting analytes [7-9]. On the other hands, micro lenses are utilized to enhance camera image quality [10] and light guide plate (LGP) also contain microstructure pattern on the surface of the material to distribute light evenly [11,12].

LGP is an essential component in many lighting systems, particularly in liquid crystal displays (LCDs). In addition, LGP are also used in a variety of other lighting applications, such as LED backlights for TVs and computer monitors, automotive lighting systems, and architectural lighting designs [13-15]. The main function of an LGP is to distribute light uniformly across the display panel, ensuring that the brightness and color consistency of the LCDs are maintained.

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The LGP works by collecting light from a light source, typically a light-emitting diode (LED) or cold cathode fluorescent lamp (CCFL) and directing it towards the edge of the plate [16]. Upgraded technology has led to the replacement of LED over CCFL, due to its mercury-free composition, high durability, broad range of color gamut choices, as well as its ability to adjust color temperature [17]. Although LED-based lighting has advantages, it also comes with a weakness: it has non-uniformity luminance difficulty. To counter the problems, LGP plays an essential role in enhancing the luminance and uniformity of LCDs [18].

The LGP is usually made of a clear polymer, such as polymethyl methacrylate (PMMA) [19,20], polycarbonate (PC) [21], polydimethylsiloxane (PDMS) [22] or optical glass [23]. It is designed with a series of microstructures patterns on its surface and these patterns serve to reflect and refract the light, causing it to bounce around the plate and disperse evenly across the display panel. By carefully controlling the size, shape, and placement of these microstructure patterns, it is possible to achieve a high level of light uniformity and efficiency.

There are a few ways to fabricate the LGP microstructure, such as by photolithography [24], hot embossing [25,26], and injection molding [27]. Photolithography is a well-established method to fabricate micro and nano scale pattern on a substrate as it guarantees a high level of precision and quality of design patterns. However, the process of fabricating LGP using this method is notoriously complex and time-consuming. This is due to the hard steps involved, including spin coating photoresist, exposing the photoresist to UV light, removing photoresist, and etching the substrate [28]. As a result, this method is categorized as high-cost method as it requires the use of specialized tools and equipment. To address this issue, researchers have explored other alternative techniques which are simpler and more cost-effective.

CO_2 laser machining seemed to be an alternative method to fabricate different type microstructure patterns such as parallel straight line, micro-dots, cross-grid, and 3D shape. It has more straight-forward steps and has low-cost production [29]. However, some researchers preferred using ultrafast lasers, such as femtosecond, picosecond and nanosecond UV lasers for engraving microstructure patterns on material surface [30,31]. These types of lasers are well-known for their high precision and accuracy, as well as ability to produce highly intricate and complex design. However, these methods are more expensive which could lead to increasing LGP fabrication costs. Moreover, conventional problem such as debris, bulge and microcracks are possible to occurred during the whole process. Comparing the advantages and drawbacks, using CO_2 laser is more practical than ultrafast lasers.

Several previous studies have investigated the effect of CO_2 laser processing on polymers. For instance, the investigation and analytical modeling of multi-pass CO_2 laser processing on PMMA had been studied [32]. A similar group of researchers then proposed a suitable CO_2 based technique for microchannel fabrication on PMMA [33]. Particularly, the influences of different numbers of CO_2 laser passes on microchannel width, depth, heat affected zone (HAZ) and surface roughness were investigated using different power settings. The effect of laser power, laser scanning speed and number of laser passes on geometrical error of the three-dimensional cavity shape during the CO_2 laser structuring on PMMA substrate was examined theoretically and experimentally [34]. However, the detailed investigation of CO_2 laser processing on polymer for application of light guide plate (LGP) is still lacking and needs further investigation. Therefore, in this study, we explored the potential of CO_2 direct laser structuring to fabricate a custom-made LGP on PMMA material with micro-dots pattern. By adjusting the laser parameters, such as laser power, and laser scanning speed, we can control the physical characteristics of micro-dots, including diameter, height, and shape, with high precision and accuracy. Then a relationship between laser parameters with formation of micro-dots were investigated, as well as luminance of the LGP with different pitch.

2. Methodology

In this study, micro-dots patterns were fabricated on PMMA material using a commercial CO_2 laser with a maximum power of 30 W and a frequency wavelength of infrared light of 10.64 µm. PMMA has a transformation point (T_g) of 115 °C, with a transmittance of about 92% and a refractive index of 1.49. The molecular weight of the PMMA is approximately 120 kDa. The 2 mm thickness PMMA was cut into dimensions of 50 x 40 mm using a similar laser system by employing maximum laser power of 30 W and laser scanning speed of 5 mm/sec. Various precautions were taken to ensure the quality of the fabricated parts, such as wiping the material clean with a microfiber cloth prior to the experiment to avoid leaving fingerprints and using a blower to remove any dust. Additionally, a pair of tweezers was used to handle the material during the experiment to maintain its cleanliness.

Figure 1 depicts the schematic diagram of the experimental setup and the top view of the micro-dots pattern design. The PMMA substrate was meticulously positioned beneath the focusing lens with the aid of tweezers. Subsequently, the commercial CO_2 laser was linked to a personal computer, where the EZCAD software was employed to design the micro-dots pattern and configure the laser parameters.

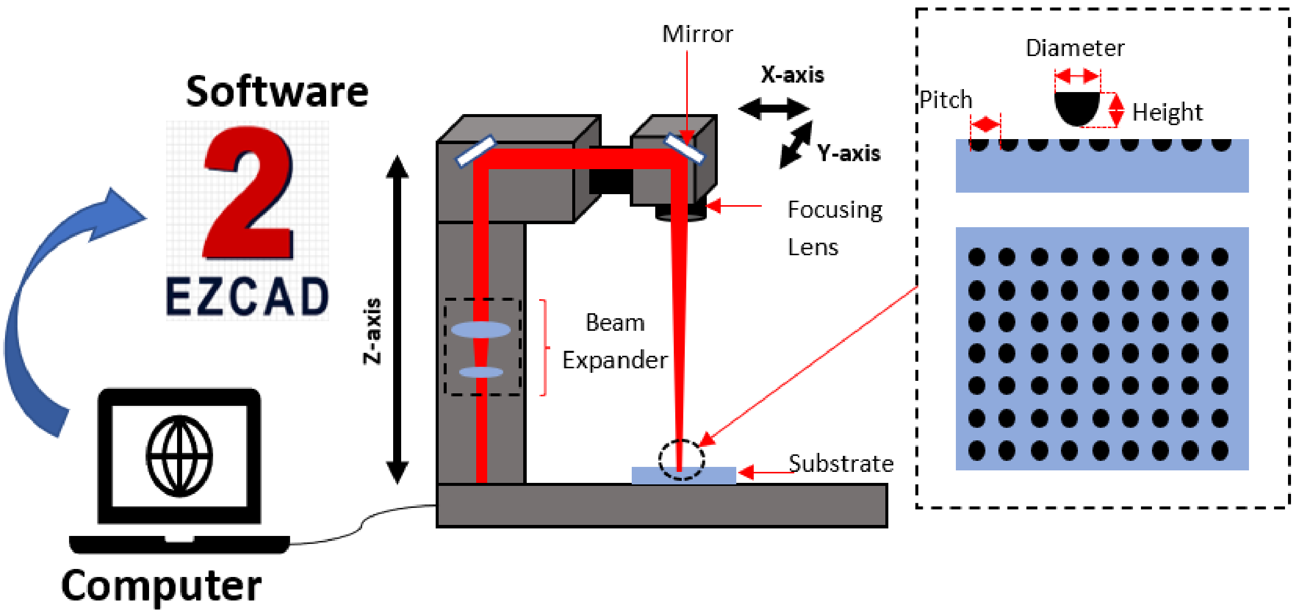


Fig. 1. Schematic diagram for the patterning of micro-dots using direct CO_2 laser structuring

The study involved conducting two experiments to investigate the formation of micro-dots design using a laser-based process. The primary focus of the study was to explore the impact of two specific laser parameters on the formation of micro-dots. The first experiment aimed to examine the effects of laser power and laser scanning speed on the formation of micro-dots. Different values of laser power such as 2, 4, 6, 8 W with constant laser scanning speed of 1500 mmsec^{-1} and laser scanning speed of 1000 – 2500 mmsec^{-1} with constant laser power of 2 W were used in each trial to evaluate the impact of these variables on the size, shape, and distribution of the micro-dots, as well as the overall quality. The 3D shape and cross-section of the micro-dots can be observed and measured using Olympus 5000 3D laser scanning confocal microscope (LSCM).

While the second experiment conducted in this study aimed to examine the effect of different pitch sizes on the luminosity of the micro-dots. In this experiment, four different micro-dots pitch sizes, 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm, were used to investigate the effect of micro-dots pitch size to luminance of the LGP. The pitch size refers to the distance between each dot in a regular pattern of dots. A LED (light-emitting diode) was used as the source of the light in this experiment. The LED strip as the single light source was placed at the edge of the polymer with micropattern surface. Then, the luminance of each of the pitches were measured by SM208 luminance meter. Figure 2 shows the schematic diagram for the measurement of the luminance reading from the LGP using SM208 luminance meter.

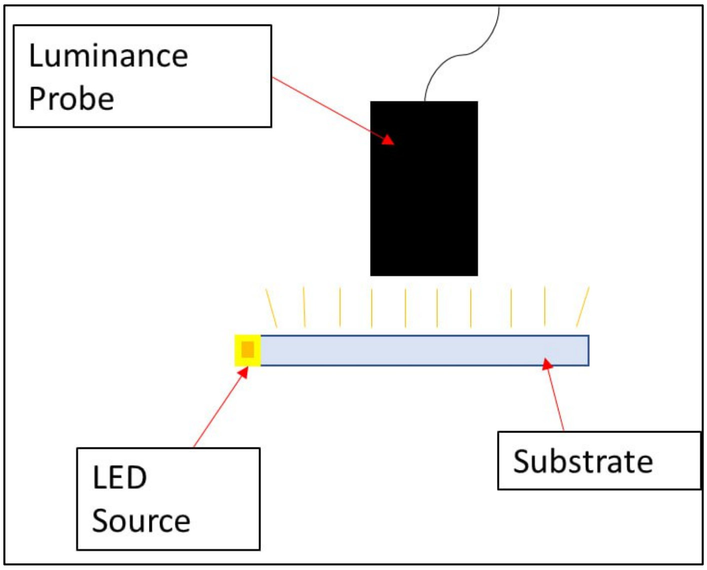


Fig. 2. Schematic diagram for the measurement of the luminance reading using SM208 luminance meter

3. Results

3.1 Effect of Laser Power to the Formation of Micro-dots

Figure 3 shows the LSCM top view image and cross-section profile of the micro-dots pattern on the PMMA substrate. The top view image provides a clear visual representation of the patterned structure, while the 2-dimensional (2D) cross-section profile provides information about the height and diameter of the micro-dots. The pitch of all the micro-dots shown below was 1 mm. Clearly, the micro-dots are evenly spaced and have a uniform diameter, further confirming the precision and consistent of the laser structuring process.

However, upon close observation, the micro-dots shapes manifest as both circular and elliptical forms as shown by the enlarged LSCM top view image in Figure 4. For instance, at a laser power of 2 W and a constant laser scanning speed of 1500 mmsec^{-1}, the shape of the micro-dots was rounded and circular in shape. While at a higher laser power such as 6 W, the shape of the micro-dots transformed to a more elongated shape, which is elliptical form. This effect became more pronounced at the highest laser power of 8 W, where the elliptical shape was prominently can be seen. Numerous observations of micro-dots with elliptical shape were also has been reported in previous study [35-37].

This variation in shapes is due to the variation of laser parameters and the material properties. The circular shape represents a more centralized energy deposition during laser ablation, resulting in a more evenly distributed form. Conversely, the elliptical shapes were due to the directional characteristics of the laser beam, impacting the elongation shape of the micro-dots [38].

Moreover, from the side view, the micro-dots demonstrate V-shaped structure. This is due to the Gaussian distribution of the laser beam, which contributes to a particular intensity distribution across the pattern. The Gaussian profile produces a higher concentration of energy at the centre of the micro-dots' formation, creating more focused and intense laser impact at the central point. Consequently, this higher intensity at the centre induces increased energy deposition, causing the central area of the micro-dots to have greater depth compared to the surrounding regions [39,40]. By varying the laser intensity and laser parameters across the formation of the micro-dots, a difference of depth can be achieved.

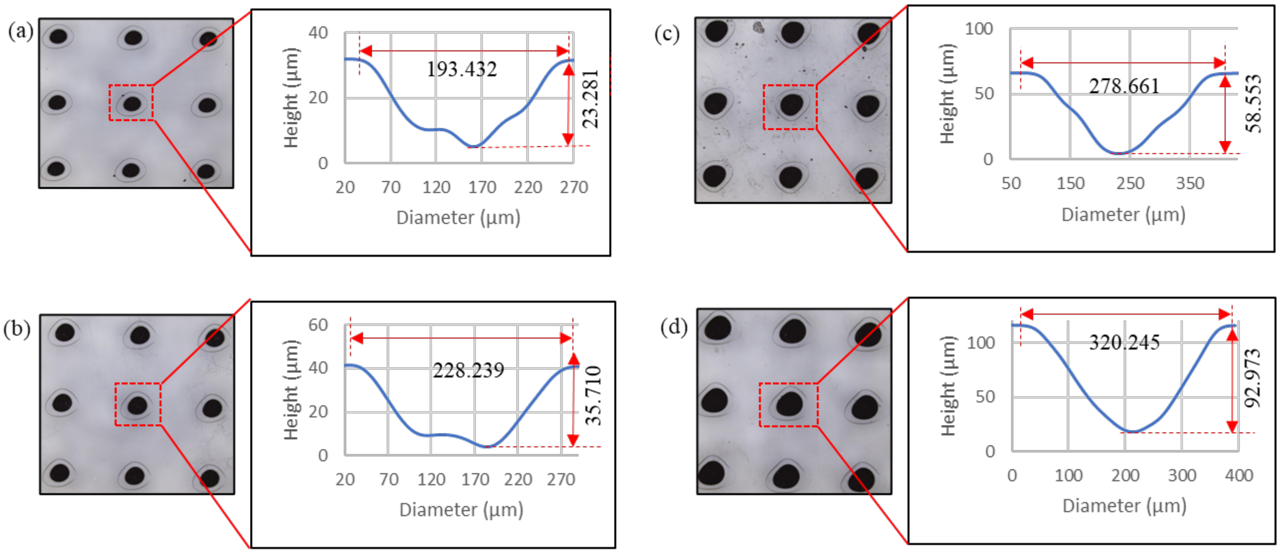


Fig. 3. LSCM top view image of the direct laser structured micro-dots (left) and its corresponding LSCM cross section profile (right) at different laser power and constant scanning speed of 1500 mmsec^{-1} (a) 2 W (b) 4 W (c) 6 W and (d) at laser power 8 W

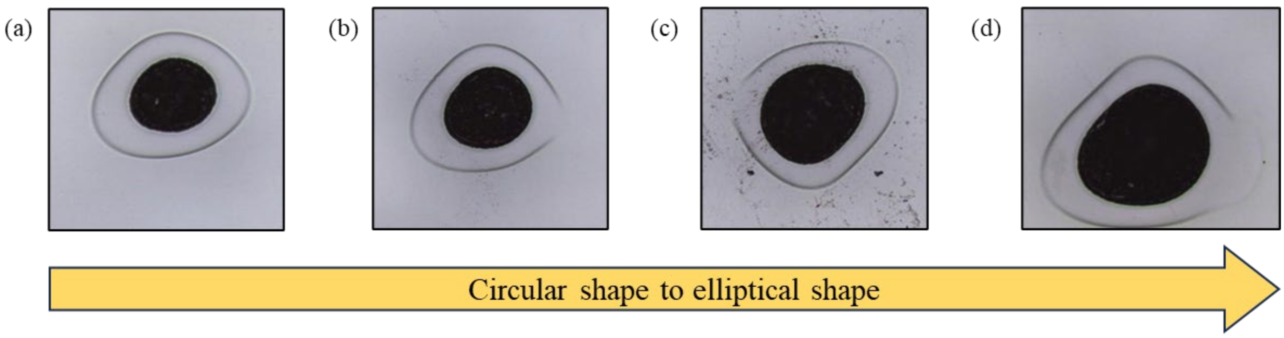


Fig. 4. The enlargement of LSCM top view image of the micro-dots from laser power of (a) 2 W (left), (b) 4 W, (c) 6 W to the highest laser power of (d) 8 W (right). These photo images show that the shape of the micro-dots evolved from circular shape to elliptical shape as the laser power increases

Figure 5 shows the illustration of the HAZ along the outer ring of the micro-dots. From the top view perspective, it could be clearly seen that HAZ developed around the micro-dots for all the laser power setting used in the experiment, from 2W to 8 W. The HAZ refers to the region in the substrate that experiences elevated temperature, but remain below the melting point [41]. This non-melted area of the substrate undergone changes in metallurgical structure, leading to changes in material properties, physical properties, hardening or softening as a result of being exposed to high temperatures [42]. The width of the HAZ is influences by various on factors, particularly thermal diffusivity. Thermal diffusivity represents the rate of heat travels through a substrate. The higher the thermal diffusivity, the higher the cooling rate and results to a small HAZ in the substrate [43].

Additionally, the width and characteristics of the HAZ can be vary based on other factors such as intensity of heat, material properties and the duration of pulse [44].

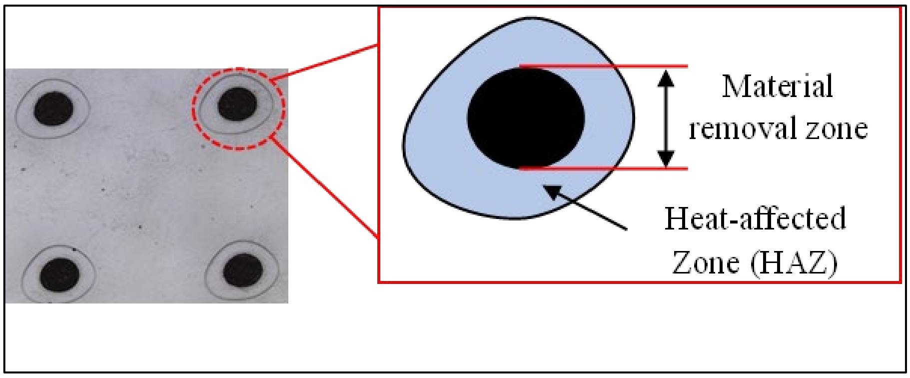
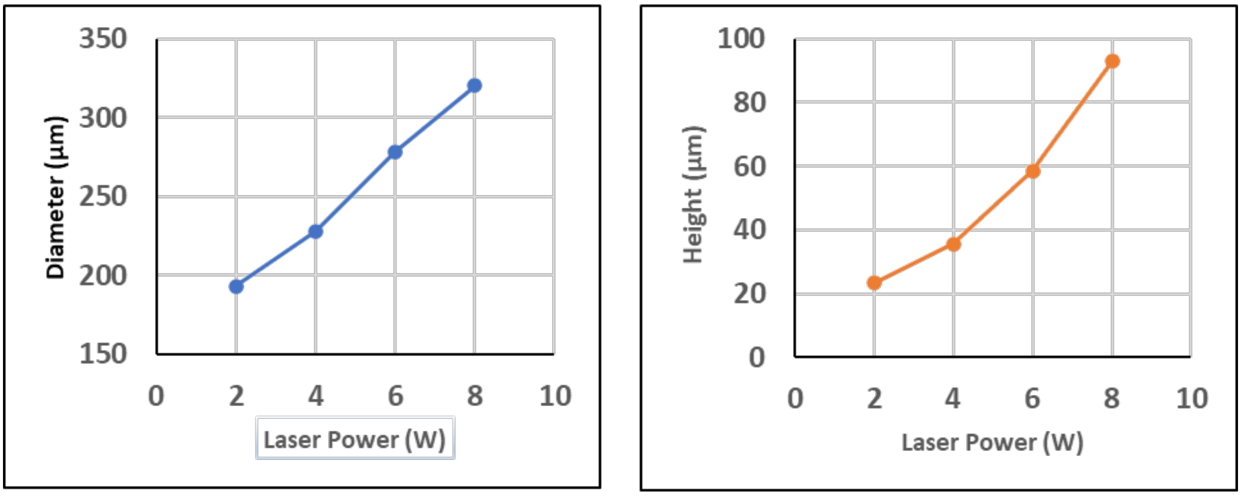


Fig. 5. LSCM image (left) and the illustration (right) of the presence of the heat-affected zone (HAZ) along the outer rings of the micro-dots

Figure 6 (a) and Figure 6 (b) shows the plot of micro-dots diameter and micro-dots height as a function of different laser power, respectively. Obviously, there is a clear correlation between laser power and the laser structured micro-dots diameter and height. Both the diameter and height of the micro-dots increase as the laser power increase. For instance, the diameter and height of the micro-dots at 2 W was 193.27 µm and 23.281 µm respectively. Whereas, larger micro-dots diameter of 320.245 µm and deeper micro-dots height of 92.973 µm were obtained when the laser power was 8 W. This is because as the laser power is increased, the intensity of laser beam also increases, which leads to an increase in temperature and reduce the viscosity of the surface of the polymer [45]. This causes the material to vaporize and be ejected from the surface, creating a large and deep formation of micro-dots [46]. This shows that the desired size; diameter and height of the micro-dots can be controlled using different range of laser powers.

In this study, it should be noted that we only conducted a single-pass laser scan method in our experiments in order to investigate the formation of the micro-dots. Compared to single laser pass method, where the laser beam moves across the surface of the substrate only once, the multiple laser passes technique involves several movements of the laser beam. It is expected that the diameter and depth of the micro-dots will significantly increase when multiple laser passes are applied. This effect has been reported in various studies, including the investigation of microfluidic ratios using PMMA substrates [47] as well as the investigation on performance of laser-etched on glass and polymer light guide plate (LGP) [48,49]. In both studies, it was observed that the size of the channel increase with the increasing number of lasers passes while maintaining constant parameters such as laser density and laser scanning speed.

Overall, the important key of the observation from the analysis of these top view images is the consistent spacing and uniform diameter of the micro-dots, which confirming the precision and consistency of the laser structuring process. This highlights the potential of direct laser structuring in consistency producing micro-dots.



(a) (b)

Fig. 6. Effect of different laser power at constant scanning speed 1500 mmsec^{-1} to the formation micro-dots (a) diameter and (b) height respectively

3.2 Effect of Laser Scanning Speed to the Formation of Micro-dots

Figure 7 shows the LSCM top view image and cross-section profile of the micro-dots pattern with different laser scanning speed from 1000 – 2500 mmsec^{-1} at a constant laser power of 2 W. Figure 8 shows the variation shapes of the micro-dots. When observed at a laser scanning speed of 1000 mmsec^{-1}, it was obvious that the micro-dots did not has circular shape pattern; instead, it exhibited an elliptical form. This elliptical shape persisted even at 1500 mmsec^{-1}. However, as the laser scanning speed increase, an interesting formation occurred which is the micro-dots shape looks more circular and rounded in structure. Notably, at laser scanning speed of 2000 mmsec^{-1} and 2500 mmsec^{-1}, the micro-dots have appeared in circular shape.

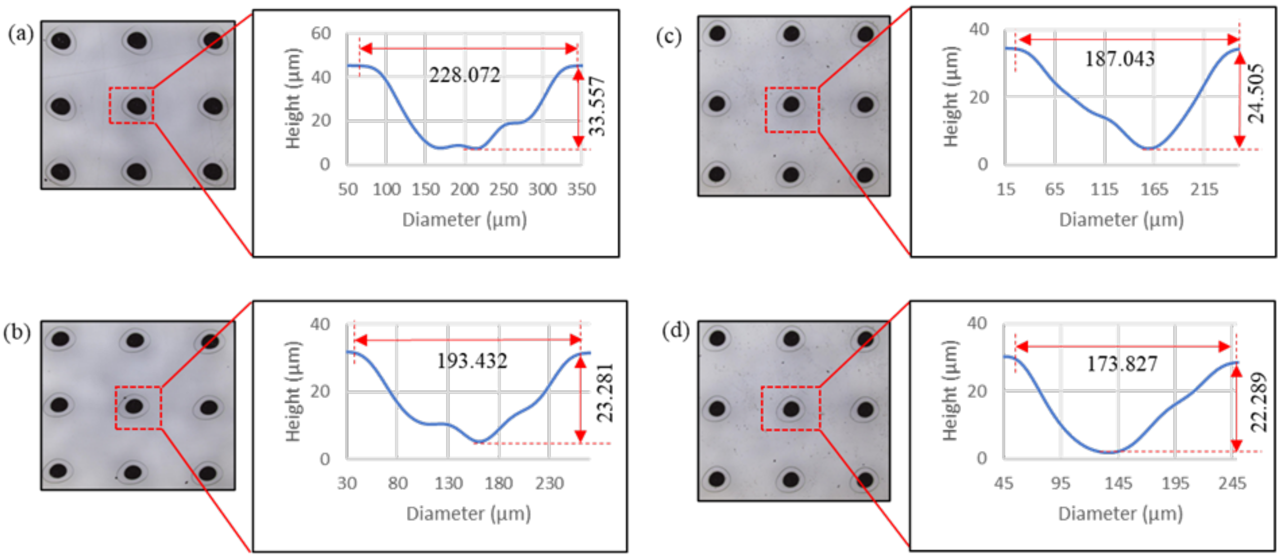


Fig. 7. LSCM top view image of the direct laser structured micro-dots (left) and its corresponding LSCM cross section profile (right) at different laser scanning speed and constant power of 2 W (a) 1000 mmsec^{-1} (b) 1500 mmsec^{-1} (c) 2000 mmsec^{-1} and (d) at laser scanning speed 2500 mmsec^{-1}

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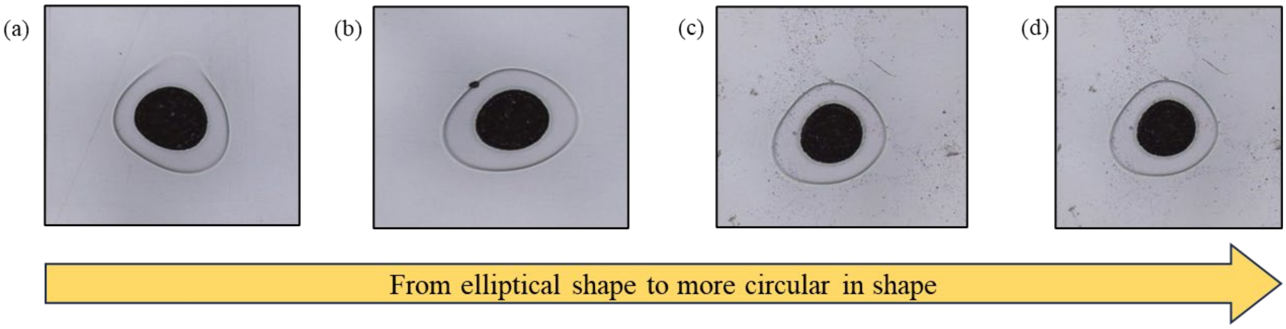
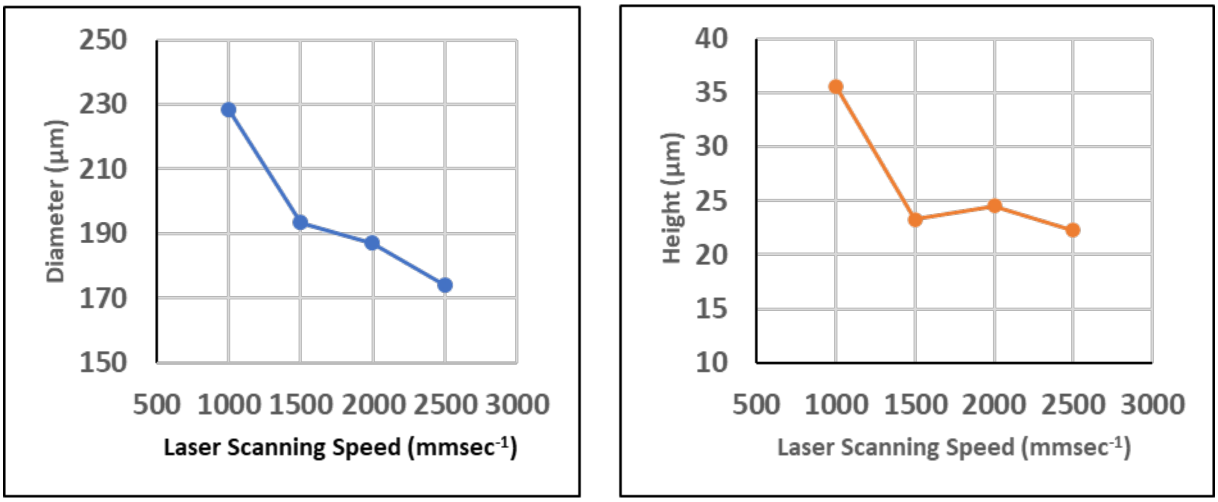


Fig. 8. The enlargement of LSCM top view image of the micro-dots from laser scanning speed of (a) 1000 mmsec^{-1}, (b) 1500 mmsec^{-1}, (c) 2000 mmsec^{-1} and (d) 3000 mmsec^{-1} (right). This photo image shows that the shape of the micro-dots become more circular in shape with the increasing of laser scanning speed

The circular shape of micro-dots at a higher laser scanning speed can be attributed to the increased energy deposition and faster heating and cooling rates. The shorter interaction time between the laser and the polymer surface might affect the heat distribution. Due to the limited exposure of time, it tends to minimize the lateral spread if heat, which create more circular solidification pattern. The reduced dwell time at higher speeds may result in a more balanced heat distribution, causing the formation of circular micro-dots.

Based on Figure 9 below, the results of our experiment have demonstrated a clear relationship between scanning speed and the physical characteristics of micro-dots formed through direct laser structuring. Specifically, as the scanning speed is increased, the size and depth of the micro-dots decrease, leading to smaller and shallower features. Similar previous finding was also reported on laser ablation of PMMA and other materials, which also found that a higher scanning speed leads to a slower ablation rate and smaller micro-dots [50]. The reason for this is that less material being ablated per unit time, which leads to a slower ablation rate and smaller micro-dots. Therefore, this mean that at a higher rate of laser scanning speed, less time exposure of the laser beam to the surface of the material will be occurred causing the diameter and the height become shallow.



(a) (b)

Fig. 9. (a) Effect of different laser scanning speed to the formation micro-dots diameter and (b) effect of different laser scanning speed to the formation of micro-dots height

3.3 Effect of Different Pitch to the Luminance of Micro-dots

Figure 10 illustrate the variation in the physical brightness of micro-dots with different pitches of 0.5, 1.0, 1.5, and 2.0 mm. We maintained a constant laser power of 2 W and a laser scanning speed of 1500 mmsec^{-1}. To ensure a comprehensive data collection, we conducted three separate luminance measurements using the luminance meter, SM208, and we derived the average luminance reading.

Figure 10 shows the photo image of the 10 x 10 micro-dots with different pitch. The analysis revealed that there is a relationship between pitch size and the brightness of the micro-dots. The micro-dots with a 0.5 mm pitch exhibited the highest brightness, followed by those with 1.0 mm, 1.5 mm, and 2.0 mm pitches. Interestingly, the larger pitch sizes produced a darker appearance of the LGP while the micro-dots with the closer pitch demonstrate greater luminosity. This physical observation highlights the influence of the pitch size of micro-dots in determining the overall brightness of the surface.

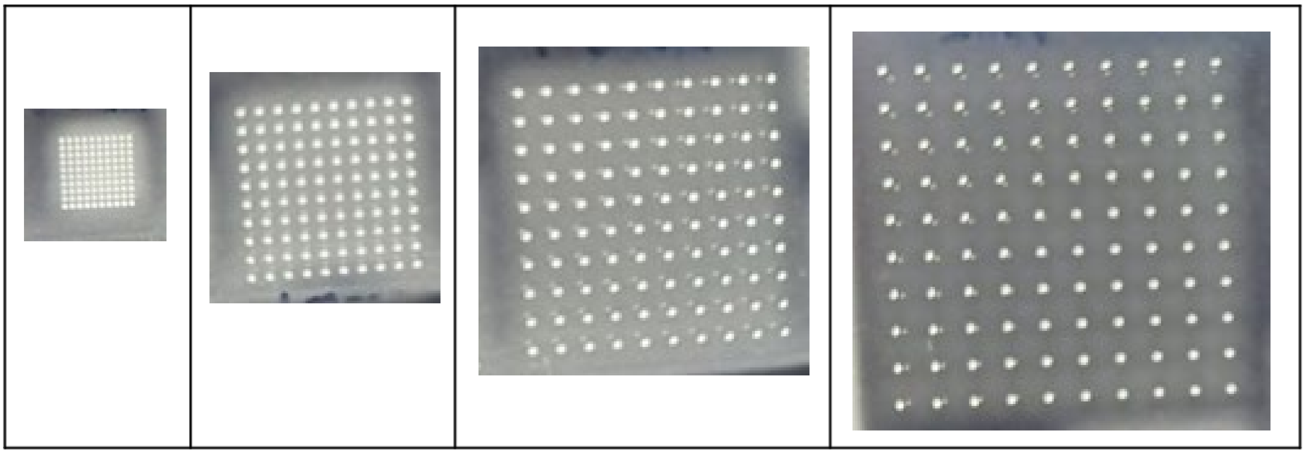


Fig. 10. Different brightness from different pitch of micro-dots

Figure 11 shows the relationship between the number of pitch and the corresponding luminance readings. From the graph below, it shows that the increasing number of pitches correlates with a reduction of luminance readings. For instance, the average luminance reading at pitch of 0.5 mm was 380.25 cd/m^2 has reduced to 103.47 cd/m^2 at pitch of 2 mm. This relationship is due to the fact that as the pitch size increases, the spacing between the micro-dots becomes widens. Consequently, it allows more lights to pass through the gaps, then reduces the overall luminosity of the micro-dots pattern [51].

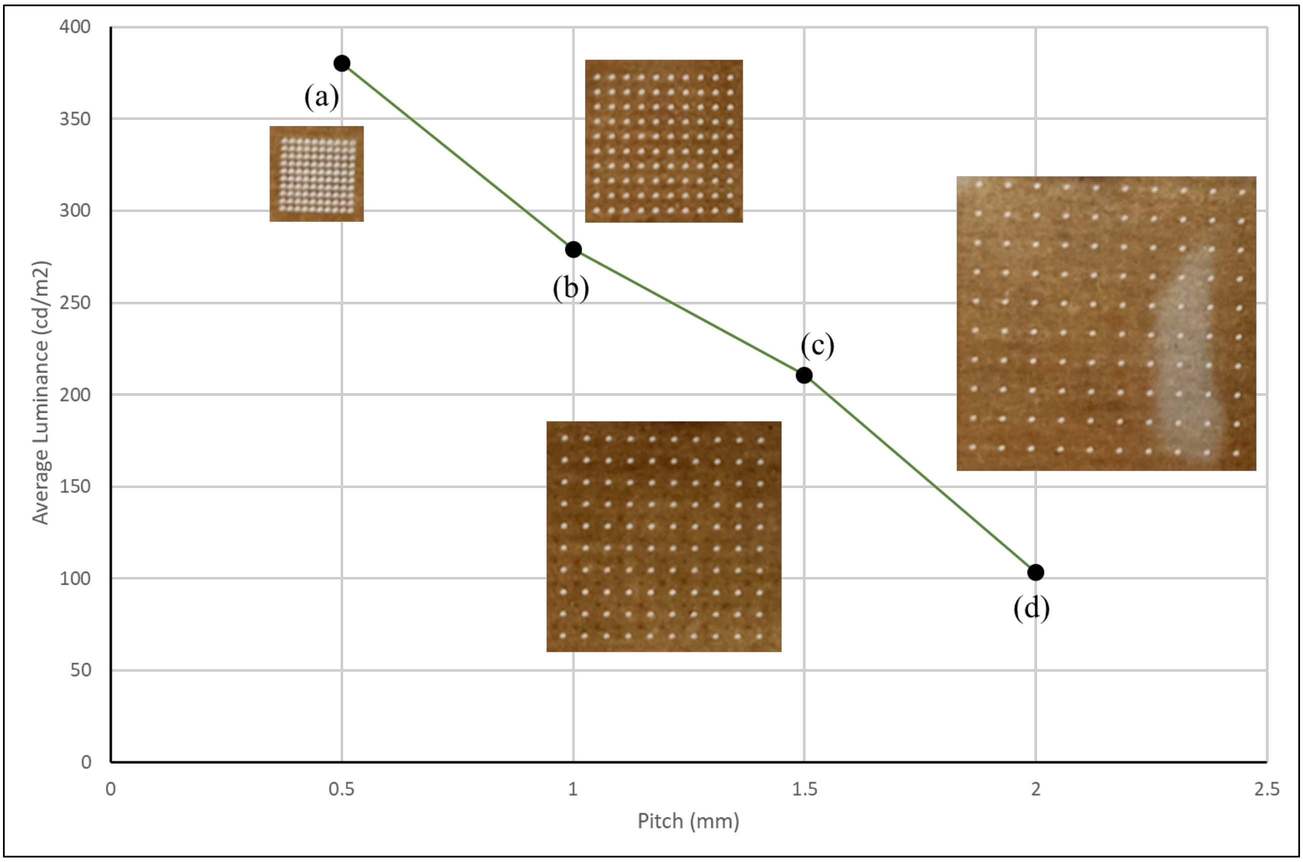


Fig. 11. Effect of different pitch to the LGP luminance

4. Conclusion

In conclusion, this study investigated the effect of different laser setting parameters on the formation of micro-dots using direct CO_2 laser structuring on PMMA substrate. The results showed that the increase of the laser power and decrease of laser scanning speed led to larger micro-dots diameters and deeper micro-dots heights. The reason behind the increase in micro-dot size with higher laser power can be attributed to the higher energy deposition into the PMMA material. This causes more significant material ablation, resulting in larger and deeper micro-dots as the laser power increases. Similarly, the decrease in micro-dot size with higher laser scanning speed is due to the reduced exposure time of the laser on each point of the material. As the laser moves more quickly across the PMMA surface, it has less time to heat and ablate the material, leading to smaller micro-dots being formed.

In addition, the distance between the micro-dots, or pitch size, had an effect on the luminosity of the micro-dots, with wider pitch resulting in lower luminosity. This phenomenon can be explained by the reduced interaction between adjacent micro-dots. With a wider pitch, there is more space between the dots, leading to less light scattering and interference, resulting in lower luminosity compared to micro-dots with a smaller pitch that have more interaction and light overlap.

These findings highlighted the importance of careful control and optimization of laser parameters when fabricating micro-dots using direct laser structuring. By adjusting the laser power, scanning speed, and pitch size, it is possible to tailor the size, depth, and luminosity of the micro-dots to meet specific requirements for various applications of LGP. Furthermore, these insights into laser parameter effects can pave the way for more cost-effective and environmentally friendly LGP fabrication, making the direct CO_2 laser structuring technique even more appealing for future technological advancements.

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