The Interaction for the pit formation on ABS with laser beam
(레이저에 의한 ABS의 홈 형성에 동반되는 상호작용)

Chosun University: Youngseop Kim, Sohee Park, Yongjin Shin
조선대학교; 김영섭, 박소희, 신용진

Abstract

Pit and rim formation on the Acrylonitrile Butadiene Styrene(ABS) plastic surface was evaluated after it was irradiated by CO_2 and Nd:YAG laser beams. Our results show that thermal effect floor was well observed at the outer wall of pit with CO_2 laser irradiated while it was not the case with Nd:YAG laser irradiated. Also the volume and depth of pit formation increase proportionally with the energy intensities of two laser irradiations, but there are significant differences in the slope, width, and FWHM of the pit formation with two types of laser irradiations. This result shows that CO_2 laser irradiation leads to better cooling contraction effect while Nd:YAG laser irradiation induces better recoil pressure effect during the interaction between ABS plastic and laser beam irradiation. The shape of the laser marking could vary significantly depending on the traveling path of molten plastic during injection molding of ABS plastic. Therefore, the selection of material and molding process can have a great impact on the performance of optical storage media.

I. Introduction

Light Amplification by Stimulated Emission of Radiation (LASER) is currently used as an innovating technology in wide variety of areas such as industry, science, medicine, and military. Especially, high power CO_2 and Nd:YAG lasers have been rapidly replacing conventional processing methods recently.' The requirements for hyper-precision processing due to the device miniaturization have accelerated advances in laser processing technology.[2,3]

Due to the recent advances in electronic data processing systems, laser has been applied to optical storage technology and has set off a wide range of researches on physical and chemical effects from the interaction between laser and material as well as optical recording media using reflexibility and optical property of material. As a result, optical recording methods utilizing the modification effect have been proposed recently.[4,6] Compared to metal, plastic has greater thermal and electrical resistance and has higher tolerance against cracking and breaking. Utilizing these merits, optical storage systems using laser marking on plastic have been pursued in recent researches.[7,9] However, modification effect and laser interaction have been only predicted indirectly by a numerical analysis, and direct measurements of modified shapes have not been available. In addition, further researches are necessary to understand material characteristics and processing phenomena fundamentally.

To better understand the optical recording mechanism macroscopically, we measured physical changes and shape modification during pit formation on the ABS plastic surface after C02 and Nd:YAG laser beam irradiations. By investigating the pit and rim formation processes from the laser spot marking, the viability of hyper-precision laser processing technique can be inferred. Also, this research will render us better understanding of data formation process on the plastic optical storage media.

2.Background

Laser spot marking is the formation of a small pit by the highly focused laser beam and generally involves three physical processes, optical absorption, heat flow, and mass motion. Upon a short temporal irradiation of laser beam, a portion of the irradiated energy is absorbed according to reflexibility of the material spontaneously.

Absorbed laser beam energy acts as a thermal source and the subsequent melting process causes heat flow around irradiated area. As a result, the surface of pit center caves in and the bulge is formed at the periphery of pit. The formation of bulge results from the black body radiation of "keyhole" formation by the collapsed surface. The proportion of absorbed laser beam energy is re-radiated outward, while the rest is transferred inside material as heat flow causing morphological changes of material. Absorbed laser beam energy decreases spontaneously at the keyhole-shaped pit. The exponential decrease of the energy follows a "Lambert-Beer" law, or $I = I_0 e^{(-\alpha d)}$, where I_0, α, and d are the irradiated beam intensity, absorption coefficient, and depth, respectively.[10] Due to the heat flow from the optical absorption, pit and rim are formed on the material surface. The formation of pit and rim can be explained by two major mechanisms, contraction upon cooling and recoil pressure.

At first, during the laser marking process, the surface tension from temperature gradient drives flow of melted material, and pit and rim are created by the contraction of melted material during cooling process. Protrusion of material can be explained by the series of processes, which include volume changes from the heat flow and surface contraction during cooling.[11,12] Because these processes occur in relatively short time period, experimental investigation is rather difficult and only the numerical approximation of processes was possible. Figures 1 (a)→(b)→(c) shows the schematic sequence of proposed pit and rim formation by the cooling contraction.

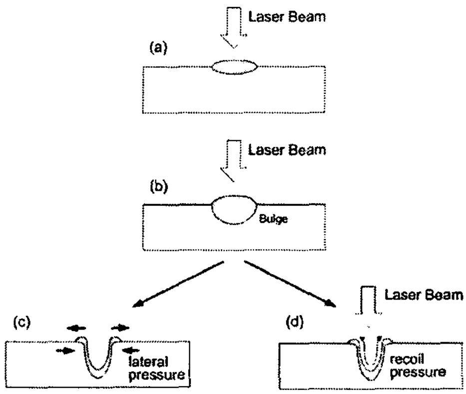

Fig. 1 . Schema of proposed mechanism: (a) molten bulge produced by local thermal expansion, (b) flow of bulge caused by surface tension (c) forming of rim by contraction upon cooling, (d) forming of rim by recoil pressure.

Recoil pressure is the second mechanism for the rim formation. The viscosity of material induces a short temporal ablation at high temperature. It also causes a volume decrease and material decomposition, which, in turn, initiates the mass motion. Therefore, viscosity induced ablation forms the pit and rim via recoil pressure. A series of pit and rim formation processes occurs almost simultaneously. Sudden temperature increase from the laser beam irradiation causes ablation during material recomposition. The recoil pressure from ablation pushes mass motion toward the surface and away from the lateral pressure, and creates the rim. As irradiation energy of the laser beam increases, the molten layer becomes thinner. Consequently, recoil pressure decreases gradually.[13,14] The rim formation mechanism involving recoil pressure is illustrated sequentially in Figures 1 (a), (b), and (d).

3.Experiments

CO_2 laser (λ = 10.64μm) with the average output power of 13 w was used for the experiment while operating in Pulse Width Modulation (PWM) mode. It has the output beam diameter of 3 mm and the beam divergence of 4 mR. The output beam from the resonator first passes through the beam expander (2.7 folds), and is incident upon ZnSe-coated X-Y galvanometer scan mirror. Finally, the reflected laser beam from the mirror is focused by the plano-convex f-θ lens (f = 154.2 mm). On the other hand, Q-switched mode Nd:YAG laser (λ = 10.64μm) has the output power of 80 w and 20 W at multi-mode and TEM_{00} mode, respectively. The beam diameters for multi and TEM_{00} modes are 4 mm and 1.2 mm, respectively, and the beam divergences are 6 mR and 2.5 mR for each mode. As with CO_2 laser, a 2.7 fold-beam expander, ZnSe-coated X-Y galvanometer scan mirror, and 225 mm focal length ZnSe plano-convex f-θ lens were used for the irradiation of laser beam. The incident energy of both C02 and Nd:YAG laser ranges between 30 mJ and 1000 mJ. The minimum incident energies of respective lasers were determined at the lowest possible energy level to investigate the pit and rim formation of the sample.

A microscope (Dongwan, OSM-1) with 40x and 80x magnifications was used to observe the surface and cross-section of the pit and rim created by the laser beam incident on the sample. To avoid possible defects on the cross section of a laser marking area and to minimize the sample collapse due to the ductility of plastic, samples were instantly frozen to -200 °c with pure liquid nitrogen and were cut by applying the sudden force on symmetrical plane around the center of pit. A digital image analysis program was used to investigate the cross sectional view of pit, rim, and thermal effect floor of the laser marking. The final images were obtained using a ×60 magnification. The digital image of the cross section was projected onto the transparent grid film (1mm scale) to acquire a relative coordination of the cross section of the sample. The shape of the cross section was approximated as a Gaussian function based on the acquired relative coordination.

Table 1 . Physical properties ofABS plastic

Classfication	Value
Density(g/cm^3)	1.04~1.06
Tensile strength(N/mm^2)	32~45
Thermal conductivity(W/mk)	0.18
Thermal diffusivity($10^{-3}cm^2/s$)	1.4
Specific heat(kJ/kgK)	1.3
Hardness	85~97
Heat deflection Temp.(℃)	95~110
Coefficient of linear expansion($K^{-1}10^6$)	60~110
Surface tension(dyne/cm)	<40
Viscosity(poise)	>1

We prepared Acrylonitrile Butadiene Styrene (ABS) plastic samples (50x20x2 mm) from common ABS resin (LG AF-302) using an injection molding technique. Physical properties of ABS plastic samples are listed in Table 1 . We used an injection molding ABS plastic as a sample because it is not only tolerant against cracking but also has higher thermal and electrical resistance compared to ceramic, glass, or metal. In addition, ABS plastic is easy to process.

4.ResultsandDiscussions

Figures 2 and 3 show the cross sectional view of the laser marking and the pit/rim shapes after CO_2 and Nd:YAG laser irradiations, respectively. Figure 2 clearly shows the thermal effect floor formation around the pit. The thermal effect floor is distributed symmetrically around the pit and pictures show that the ratio between width and depth of the pit increases as irradiation energy increases. Contrary to CO_2 laser beam marking, the thermal layer was not observed in Nd:YAG laser marking (Figure 3), and increase of the ratio between width and depth of the pit was relatively small with irradiation energy increase.

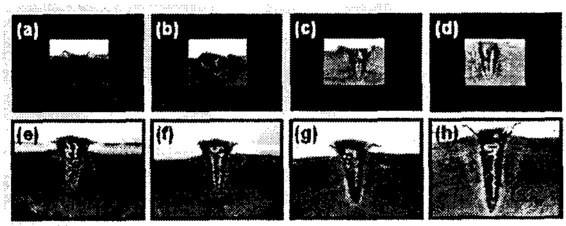

Fig. 2. The cross sectional view of ABS plastic after CO2 laser irradiation: (a) 50 mJ. (b) 100 imJ, (c)200 mJ, (d) 300 mJ, (e) 400 mJ, (0 500 mJ, (g) 750 mJ, (h) 1000 mJ ; 60x magnification.

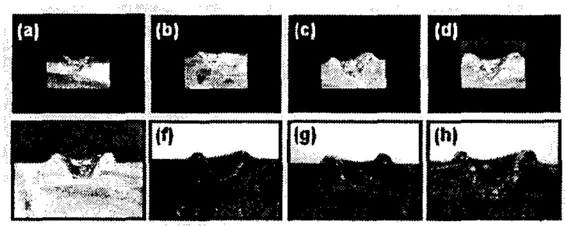

Fig. 3. The cross sectional view of ABS plastic after Nd:YAG laser irradiation; (a) 50mJ, (b) 100 mJ, (c) 200 mJ, (d) 300 mJ, (e) 400 mJ, (1) 500 mJ, (g) 750 mJ, (h) 1000 mJ ; ×60 magnification.

Changes in depth, width, and FWHM (FµûI Width at Half Maximum) are plotted as a function of the irradiation energy in Figure 4. In CO_2 laser irradiation, the depth of pit increased linearly (1.6 µm/mJ) with the energy, while increase in width was less conspicuous. The rate of increase in width slowed down after 400 mJ. The progression of FWHM was similar (~ 370 µm) to the width, and it reached its maximum at 500 mJ. Changes in depth, width, and FWHM of the pit with Nd:YAG laser irradiation were similar to CO_2 laser irradiation. The depth increased linearly (0.6 µm/mJ) with the irradiation energy. The width increased linearly up to 600 mJ and its rate of increase slowed down at higher energy level. The increase of FWHM was also linear up to 400mJ, but the rate of increase slowed down afterward reaching its maximum (630 μm) at 700 mJ.

The pit volume is also plotted as a function of the irradiation energy in Figure 5. With both CO_2 and Nd:YAG laser irradiations, pit volume increased linearly. However, there was significant difference in slopes with two types of irradiation (19.4×10^4 $\mu J^3/mJ$ for CO_2 and 9.5×10^4 $\mu m^3/mJ$ for Nd:YAG laser irradiations, respectively). This fact implies CO_2 laser with longer-wavelength exerts better cooling contraction effect while Nd:YAG laser with shorter-wavelength exerts better recoil pressure effect on ABS plastic.

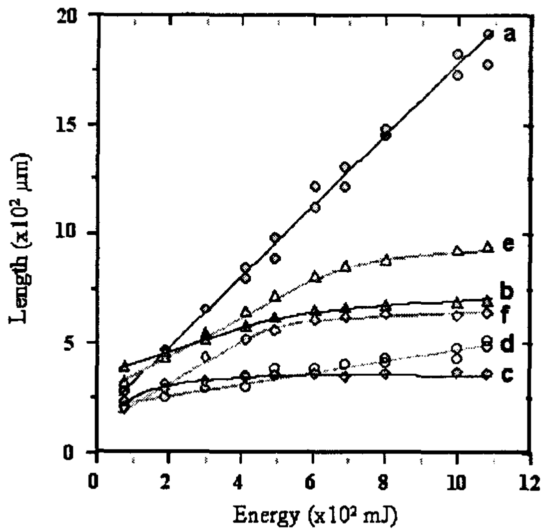

Fig. 4. Changes in depth, width, FWHM (Full Width at Half Maximum) with CO_2 and Nd:YAG laser irradiations; (a) CO_2 -Depth, (b) CO2 -Width, (c) CO2 -FWMM, (d) Nd:YAG -Depth, (e) Nd:YAG -Width, (f) Nd:YAG -FWHM.

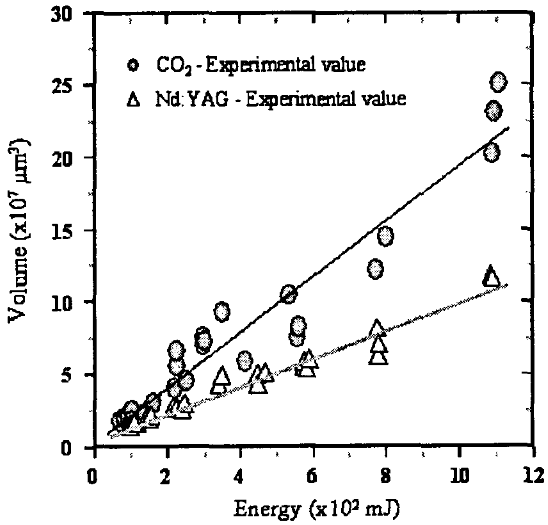

Fig. 5. The changes of pit volume with CO_2, and Nd:YAG laser irradiation.

Figure 6 shows the surface profiles of the rim during the pit formation by laser irradiations. Because ABS plastic samples were prepared by the injection molding, viscous flow of ABS resin exists inside the injection mold during fabrication. The direction of viscous flow gives rise to a direction of mass motion and a subsequent rim orientation. The prescribed direction of viscous flow also explains the asymmetry of rim formation in Figure 6. When molten plastic resin is injected through a small nozzle of the mold, the pressure difference at the nozzle creates turbulent flow of molten resin, and the turbulence results in the different orientation of rims. This different orientation of rims should not be overlooked because the shape and size of the rim play an important role in data formation of optical storage as well as those of the pit. This result demonstrates the importance of the direction of molten layer during the fabrication when plastic is used as optical data storage material.

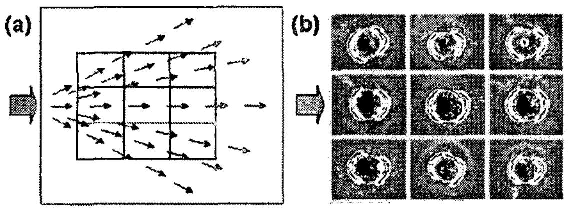

Fig. 6. Photography of laser spot marking on the surface of ABS plastic; (a) Traveling course of molten plastic in injection mould, (b) Rim's orientation by laser spot marking corresponding injection direction

5.Conclusions

We observed the formation of pit and rim on ABS plastic surface by CO_2 and Nd:YAG laser irradiations and investigated the interaction between ABS plastic and laser irradiation energy and marking mechanisms. The volume and depth of the pit are nearly proportional to irradiation energy and it shows uniform proportion of absorbed energy was used for the pit formation.

Characteristics and shapes of pits, especially slopes, differ with CO_2 and Nd:YAG laser irradiations. This fact implies CO_2 laser with longer-wavelength (λ=10.64 μm) exerts better cooling contraction effect on ABS plastic while Nd:YAG laser with shorter-wavelength (λ=1.06 μm) induces more effective recoil pressure.

In addition, we demonstrated the shape of laser marking varies significantly depending on the direction of molten plastic during fabrication. Also, the fabrication method as well as the selection of material plays an importance role when plastic is used as a base material for the optical data storage.

References

1. J. Wilson. J. F. B. Hawkes, laser principles and applications, Prentice Hall International Ltd., UK (1987).
2. R. R. Tummala and E. J. Rymaszeski, Microelectronics packaging hand book, Van Nostrand Reinhold, New York (1989).

3. Y. J. Shin and Y. G. Kang, "Laser micro-machining," J. Kor. Electric. and Electro. Mater. Engin. 14(6), 1~6(2001).
4. K. Y. Law and G. E. Johnson, "Ablative optical recording using organic dye-in-polymer thin films," J. Appl. Phys. 54(9), 4799~4805 (1983).
5. D. A. Hill and D. S, Soong, "A model for laser marking of thin organic data storage layers by short intense pulse," J. Apply. Phys.. 61, 2132~ 2135 (1987).
6. K. F. Wissbrun. "Thermal expansion and flow model for pit formation in laser marking of polymeric film optical disks," J. Apply. Phys. 62(3), 1123~1124 (1998).
7. Y. M. Noor. S.C. Tarn. L.E.N. Lim and S. Jana. "A review of the Nd:YAG laser marking of plastic and ceramic IC packages,"' J. Mater. Proce. Tec. 42(1), 95~133(1994).
8. s. H. Slivinsky and N. E. Ogle, "Laser beam interaction with plastic," J. Apply. Phys. 48(9), 3660~3664 (1977).
9. J. H. Chang, Y. J. Shin, K. W. Jeong, J. H. Lee, and J. 0. Kim, "Development of laser marking and drilling system for high speed moving object," J. Kor. Laser Tech. 101, 51~55 (20O2).
10. M. Lax, "Temperature rise induced by a laser beam," J. Apply. Phys. 48(9), 3919~3924 (1977).
11. T. s. Chung, "Pit formation during laser marking of thin organic films," J. Apply. Phys. 60(1), 55~60 (1986).
12. K. F. Wissbrun, "Thermal expansion and flow model for pit formation in laser marking of polymeric film optical disks," J. Apply. Phys. 62(3), 1123~1124 (1998).
13. J. J. Wrobel, A. B. Marchant, and D. G. Howe, "Laser marking of thin organic films." Apply. Phys. 40(11), 928~930 (1982).
14. M. C. Gupta, "A study of laser marking of thin films," J. Mater. Res 3(6), 1187~1195(1988).