Proposal of optimal process parameters for polymethylmethacryl plastic adhesion using a pulsed Nd:YAG laser

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Abstract. In this study, we propose a pulsed Nd:YAG laser system that uses a sequential charge and discharge circuit to adhere polymethylmethacryl (PMMA) plastics. Two PMMA plastics adhere to each other when the red one transmits the laser beam and the black one absorbs it. The optimal adhesion depends on several process parameters, such as the charging voltage of the capacitor, the pulse rate [in pulses per second (pps)], the velocity of the target, and the laser beam diameter. We try to optimize the adhesion process parameters from trial-and-error experiments. It has proposed that the optimal adhesion process parameters are a charging voltage of 650 V, a pulse rate of 11 pps, a target velocity of 4.20 mm/s, and a laser beam diameter of 4.00 mm in this pulsed Nd:YAG laser system. In addition, we generalize the optimal conditions for plastic adhesion, such as energy per pulse, peak power, and the velocity of the target. [DOI: 10.1117/1.3204233]

Subject terms: pulsed Nd:YAG laser; polymethylmethacryl (PMMA) plastic adhesion; optimal adhesion process parameters.

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1 Introduction

Laser applications are being widely used in material processing, industrial devices, and various medical equipment.[1–5] In material processing, the application scope of laser technologies continues to expand, and more refined and precise processing is required in industrial sites. The output types of laser systems are classified as either pulsed or continuous wave, and both are popular in material processing. Each has an independent area of application depending on its characteristics.[6,7]

One of the material processing methods is the laser welding technique of plastics and acrylics. The aspect of the pulsed laser welding technique was described by Parkin.[8] He insisted that it was flexible and could permit multiple packing-shapes to be made in a single production line, providing a major advantage over a conventional heat-sealing system.

There are many lasers to weld plastics or acrylics. The CO_2 laser is used for welding thin polyolefin film (up to 0.1 mm thickness) with 100 W of power.[9] The output beam absorption starts from the surface layer, and then the energy intensity decreases as the welding interface becomes more distant from the surface layer; thus, it cannot be used for the adhesion of thick plastics. The diode laser is also used for the adhesion of plastics with a power density of 0.6 J/mm^2, and a high-power (4 kW) Nd:YAG laser is also used to weld plastics.[10,11]

All the above-mentioned systems are the continuous-wave type. In these cases, the heat is provided into the surface of plastic continuously. This causes a wider heat-affected zone on the plastic. Thus, it is impossible to apply to the small area of plastic adhesion. However, it is possible to adhere small areas of plastic in the pulsed laser system because of lower heat accumulation and a lower heat-affected zone.[12] Also, there is lower heat damage in the case of the pulsed laser system.

In this study, we propose a pulsed Nd:YAG laser system that can easily adhere two polymethylmethacryl (PMMA) plastics, but the strength of adhesion varies with several process conditions related to the laser system. Therefore, process parameters for optimal adhesion are determined from many trial-and-error experiments, and the characteristics of the laser beam, such as peak power and energy pulse, are investigated when the optimal adhesion of two PMMAs occurs.

2 Experiments

2.1 *Pulsed Nd:YAG Laser System*

Our pulsed Nd:YAG laser system used to adhere two PMMAs is composed of a single elliptic cavity containing a xenon flash lamp and a Nd:YAG rod, two mirrors, a water-cooling system, a power supply, and an output controller. The xenon flash lamp and the rod are placed at the two focal points of the ellipse. Therefore, the light is transferred effectively from the flash lamp to the rod. The two mirrors consist of a full mirror and a partial mirror. The full mirror is a concave mirror that has 99.5% reflectivity, and the partial mirror is a plane mirror that has 80% reflectivity. Figure 1 shows the schematic diagram of our pulsed Nd:YAG laser system.

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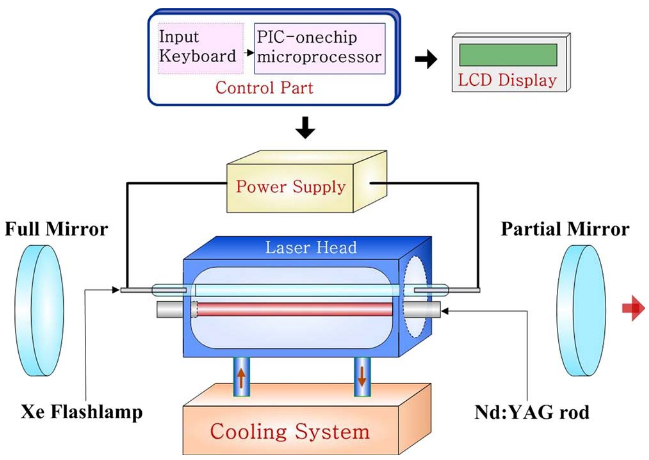

Fig. 1 Schematic diagram of our pulsed Nd:YAG laser system.

The specially designed power supply is used to operate our pulsed Nd:YAG laser system. This includes a sequential charge and discharge circuit (SCADC). The operation sequence of the SCADC is as follows, and its details are shown in Fig. 2:

1. Apply 1 kV dc to both ends of the xenon flash lamp with the simmer circuit and then push the simmer trigger switch. After that, the streamer discharge is sustained in the flash lamp.
2. When a silicon control rectifier (SCR) S1 is turned on, the input energy is stored in capacitor C1, and then a SCR S2 is turned on. At this moment, the energy stored in capacitor C1 is delivered and the flash lamp is flashed.

Two SCR trigger signals are achieved by using a Microchip 16F877 in the output control. The microcontroller is programmed to precisely coordinate the delivery of the trigger signals at the appropriate pulse rate.

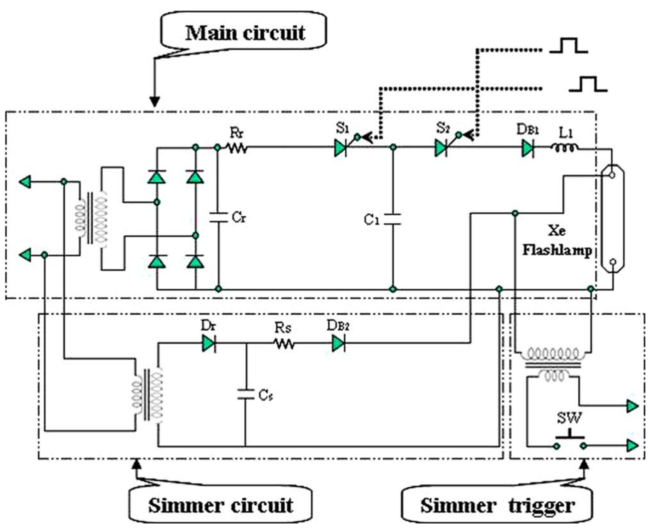

Fig. 2 Sequential charge and discharge circuit.

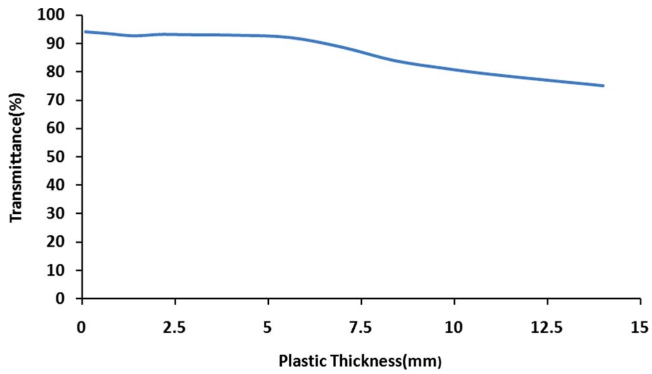

Fig. 3 Relationship between the thickness and transmittance of red PMMA on 1064 nm wavelength.

2.2 *Plastic Characteristics*

PMMA used in this experiment has applied to many industrial sites. Two kinds of PMMA are used in this experiment: one is a transparent red plastic that is 2.8 mm thick and the other is an opaque black plastic that is 2.0 mm thick. The former is used as the top layer, and the latter is used as the bottom layer. The transmittance of red plastic is an important plastic characteristic because this affects the intensity of the irradiated laser beam. Figure 3 is the relationship between the thickness and the transmittance of red PMMA on 1064-nm laser beam. As shown in Fig. 3, this plastic has >90% transmittance until ~7.0 mm thickness. This means that most energy of the laser beam is transferred to the bottom layer through red PMMA in the range of 7.0 mm thickness. These two plastics have to be adhered as close as possible to each other because the air gap between both plates interrupts the heat transfer with loss. In this experiment, the air gap between both plates is removed by using a strong chuck to minimize the problem of contact between two plastics. And the melting point of PMMA used in this experiment is ~70 °C.

2.3 *Plastic Adhesion and Process Parameters*

When the laser beam irradiates the top surface, the transmittance of top plastic prevents the laser beam from being absorbed; thus, most of the laser energy is absorbed in the adjacent black plastic. Its beam energy is converted from light to heat at the contact of two plastics, and this heat energy causes the adhesion to develop. Thus, the laser beam energy is one of the dominant factors in the adhesion of two plastics, and the quality of plastic adhesion depends on the amount of laser beam energy. The amount of laser beam energy is calculated by

$$\text{Energy} = \frac{1}{2}CV^2 \times R_p \times \eta. \tag{1}$$

In Eq. (1), C is the capacitance, V is the charging voltage, R_p is the predetermined pulse rate, and η is the energy converting efficiency of the laser system. The output energy is changed by adjusting the charging voltage and the pulse rate; thus, the charging voltage and the pulse rate are the primary process parameters associated with the adhesion of two plastics.

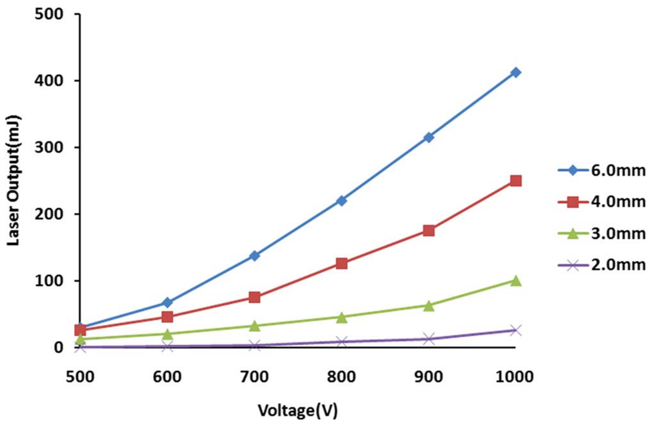

Fig. 4 Laser output energy for the beam diameter.

The beam diameter also has an effect on the quality of plastic adhesion. This parameter determines the mode and energy distribution of laser beam. Therefore, the status on adhesion is varied as the beam diameter changes because energy distribution on each beam diameter is different. Thus, the beam diameter is also an important process parameter for the adhesion of two plastic plates. The original laser beam size is 6.00 mm, and its size is adjusted by using a pinhole in this experiment.

In addition, the velocity of the target affects the status of plastic adhesion. A long irradiation of the laser beam to the target causes deformations of plastic. Thus, if the velocity of the target is slow, then the plastics start to deform. On the other hand, if the velocity of the target is fast, then there is no sufficient time to melt plastic. And then, the plastic adhesion is failed or the adhesion strength is weak in this case. Therefore, the proper velocity of the target is also an important process parameter on two plastics adhesion. The velocity of the target is controlled by using a motor (KM 3429C, GUGJE Geared Motor Co. Ltd.).

Four parameters that have a large effect on the adhesion of two PMMA plastics are determined: the charging voltage, the pulse rate, the beam diameter, and the velocity of the target. That is, the adhesion of two plastics is accomplished with a good adhesive strength and good surface appearance if the four parameters are optimal.

3 Experimental Results and Discussion

Pulse duration in this experiment is 300 μs, and full width at half maximum is 150 μs. The pulse duration is dependent on values of inductors and capacitors used in SCADC. Therefore, the pulse duration is constant because values of inductors and capacitors are not changed during the operation of our pulsed Nd:YAG laser system, and a cycle of pulse is 1 s in the case of one pulse per second (pps) and 500 ms in the case of 2 pps. Consequently, as the value of pulse per second increases, the cycle of pulse reduces at half the previous value. But the value of the ON time is constant at 300 μs. Thus, the duty cycle increases as the value of pulse per second increases.

Energy amount and distribution of a laser beam depend on the beam diameter. Figure 4 shows the laser output energy for the beam diameter. The laser output energy increases as the beam diameter increases because the loss of the laser beam decreases. The laser output energy is low in the range of all charging voltages when the beam size is small. The large output energy is needed to adhere two plastics, and this is obtained when the beam size is large. But, in general, the energy intensity distribution is not focused to the center of beam diameter as the beam diameter increases. Figure 5 shows the energy intensity distribution at the beam diameter of 4.00 and 6.00 mm. The energy distribution is not proper for plastic adhesion in the case of 6.00 mm (the original beam diameter) because the energy is dispersed from the center of the beam diameter. The energy intensity distribution is more focused at the beam diameter of 4.00 mm than at the beam diameter of 6.00 mm, and this distribution shape is like Gaussian distribution. As the result, the optimal laser beam diameter is determined as 4.00 mm because this beam diameter that has a more focused energy distribution with large energy for the plastic adhesion.

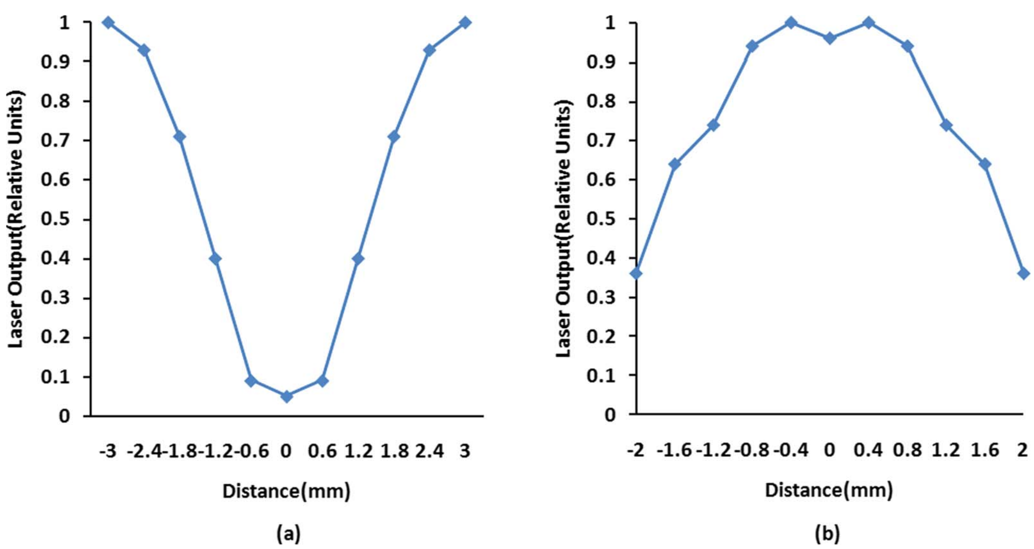

Fig. 5 Energy intensity distribution at the beam diameter of (a) 6.00 and (b) 4.00 mm.

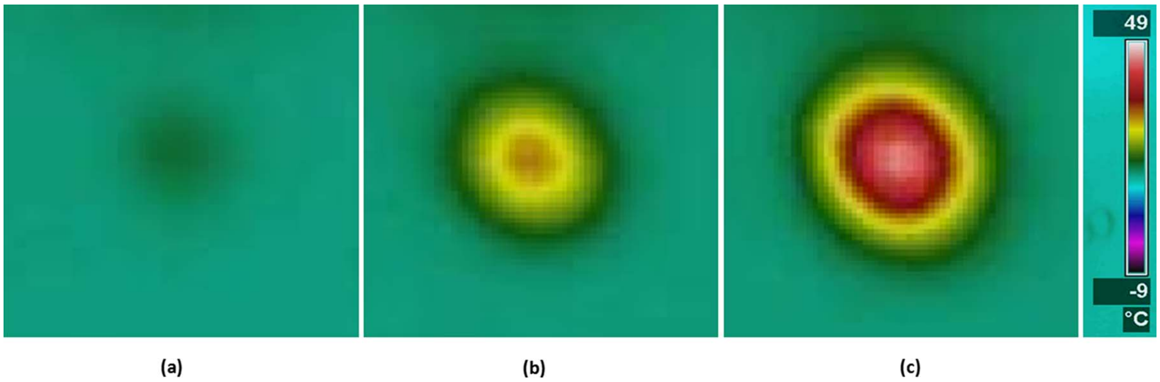

Fig. 6 Temperature distribution when the beam diameter is 4.00 mm with irradiation time: (a) 0, (b) 5, and (c) 10 s.

Figure 6 shows the temperature distribution of that case at the contact surface of plastics when the beam diameter is 4.00 mm. That is measured by the infrared camera (ThermaCam p20, FLIR Thermal Infrared Camera Systems, Inc.). The energy of the irradiated laser beam is focused on the area near the beam center, which is called the heat-affected zone (HAZ). As shown in Fig. 6, the HAZ is increased as time passes because the Gaussian energy distribution gives the focused energy to the HAZ, and this causes a continuous temperature rise on the HAZ.

The charging voltage of the capacitor and the pulse rate are adjusted with the optimal laser beam diameter to determine the optimal charging voltage of the capacitor and the optimal pulse rate. The charging voltage of the capacitor is varied from 500 to 800 V by the step voltage of 25 V. The two plastics do not adhere to each other as the voltage is varied from 500 to 550 V at any working time because the laser output energy is low, and the deformation of two plastics occurs at $>$725 V as soon as the laser beam is irradiated on the contact surface of plastics. The plastic adhesion can be occurred in the range between 575 and 700 V.

Figure 7 presents the relationship between the adhesion diameter and the working time. The adhesion diameter increases as the energy absorption increases. But the expansion of the adhesion diameter is saturated from some points. As shown in Fig. 7, the saturated adhesion diameter is small in the range between 575 and 625 V. This means that the adhesion is occurred in this range, but the strength of adhesion is weak and two plastics are separated easily. On the other hand, the saturated adhesion diameter is larger than previous one in the range between 650 and 700 V. This means that the strength of adhesion is strong and the separation of two plastics is difficult. In this case, the working time is 5 s to start the saturation of the adhesion diameter. Therefore, the target is fixed and the working time is chosen as 5 s during the experiment to determine the optimal charging voltage and pulse rate.

Table 1 shows the energy per pulse and peak power on each charging voltage, and these are acquired by Eq. (1). The capacitance is 360 μF in this SCADC circuit, and the energy converting efficiency of this Nd:YAG laser system is $\sim$2%. As shown in Table 1, the adhesion does not occur below the energy of 1.5 J per pulse and the peak power of 10 kW. The deformation of plastic occurs at $>$1.8 J per pulse and that of 12 kW.

The plastic adhesion occurs between 1.5 and 1.8 J per pulse and between the peak power of 10 k and that of 12 kW. Therefore, the pulse rate is varied when the charging voltage of capacitor is adjusted only from 650 to 725 V.

After producing numerous samples of fused plastics, the adhesion strength is measured using a force gauge (AFG-1000N, Mecmesin) with the Versa-Test stand. Figure 8 shows the relationship between the adhesion strength and the pulse rate. Actually, as the pulses per second increases, the adhesion strength also increases up to some points. These points are 11 pps at 650 V, 9 pps at 675 V, and 7 pps at 700 V. The adhesion strength becomes weaker as pulses per second goes up above these points. This is caused by the deformation of the plastic. The plastic starts to deform when the melting process converts to the evapo-

Table 1 The energy per pulse and peak power on each charging voltage

Plastic status	Detachment		Adhesion			Deformation	
Charging voltage (V)	600	625	650	675	700	725	750
Energy per pulse (J)	1.30	1.41	1.52	1.64	1.76	1.89	2.03
Peak power (kW)	8.67	9.40	10.13	10.93	11.73	12.60	13.53

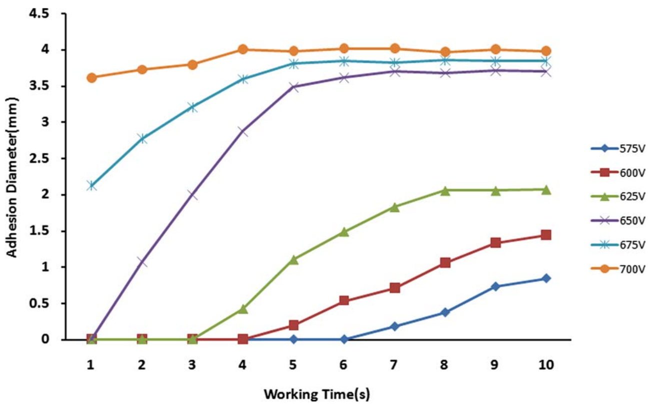

Fig. 7 Relationship between the adhesion diameter and the working time.

rating process due to high energy intensity and temperature. The deformed plastics is separated each other easily because the contact surface becomes white and rough as shown in Fig. 9. As the charging voltage increases, a slope from the starting point to the strongest adhesion point becomes steeper. This means that the adhesion strength is accomplished faster because the energy per pulse and peak power increase as the charging voltage goes up. As shown in Fig. 8, there is a point of the strongest adhesion in each voltage. Among them, the strongest adhesion strength is obtained as 7.12 kgf (69.78 N) at the case of 11 pps at 650 V. Therefore, the optimal charging voltage and pulse rate are determined 650 V at 11 pps.

The velocity of the target is not the essential parameter to affect the status of the plastic adhesion if the target is fixed because there is no velocity in this case. But this process parameter has an effect on the status of plastic adhesion when the target moves. The adhesion strength becomes weaker because the heat accumulation is discontinuous when the target is much too fast. Otherwise, plastics are easily deformed when the target is much too slow because the energy level of each pulse that causes the fusion of

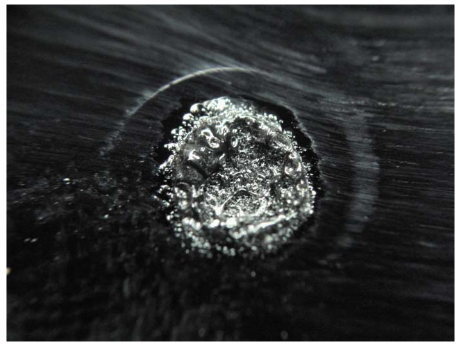

Fig. 9 Deformation contact surface of plastic.

plastics can be overlapped. The overlapping rate is considered to determine the optimal target velocity. The overlapping rate (OL) is determined by

$$\mathrm{OL}(\%) = \frac{D - B}{D} \times 100, \quad (2)$$

where D is the beam diameter and B is the bite size. The target velocity and the pulse rate affect the bite size and OL. Consequently, the bite size decreases and the OL increases as the target velocity and the pulse rate increase, and vice versa. The quality of continuous adhesion line is same in terms of the shape if the value of the OL is same. But the strength of the adhesion is different. It depends on the pulse rate and the irradiated energy intensity. Thus, the optimal target velocity is determined at the optimal conditions in case of the fixed target: the beam diameter is 4.00 mm, the charging voltage is 650 V, and the pulse rate is 11 pps.

Figure 10 shows the relationship between target velocity and OL at the optimal conditions in case of the fixed target. As the target velocity increases, the OL tends to decrease. When the OL is 90.5%, the optimal adhesion status without plastic deformation is acquired and the target velocity is 4.20 mm/s in this case. Therefore, the optimal velocity of the target is determined as 4.20 mm/s.

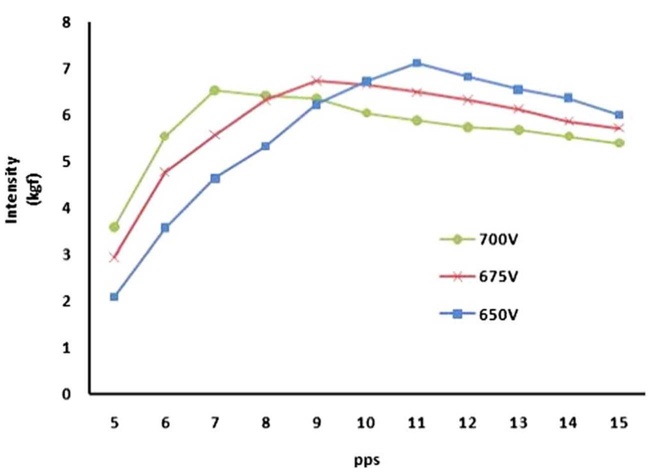

Fig. 8 Relationship between the adhesion strength and the pulse rate.

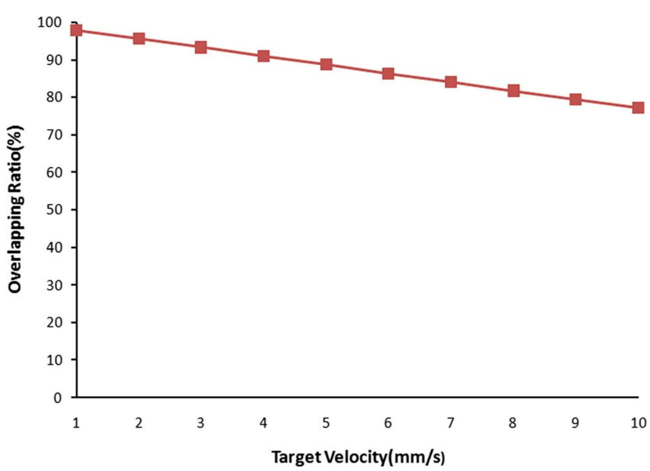

Fig. 10 Relationship between the target velocity and OL at the next condition: the beam diameter is 4.00 mm, charging voltage is 650 V, and pulse rate is 11 pps.

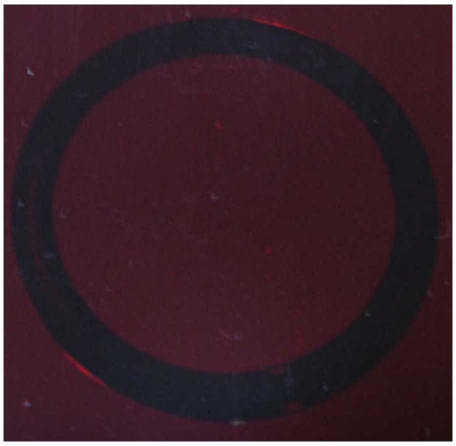

Fig. 11 Sample adhesion plastics using the optimal parameters: 650 V, 11 pps, 4.2 mm/s, and 4.00 mm.

Figure 11 shows a sample of the adhered plastics, and Fig. 12 shows scanning electron microscope [(SEM), Hitachi S-4200, Hitachi] photographs of the contact surface between the transparent red plastic and the opaque black plastic. These are the optimal results because there is no plastic deformation and the adhesion strength is the greatest. Consequently, the optimal adhesion process parameters are determined as 650 V, 11 pps, 4.20 mm/s, and 4.00 mm in this pulsed Nd:YAG laser system.

4 Conclusion

A pulsed Nd:YAG laser system was proposed to adhere two PMMA plastics in this study, and the SCADC was applied to the power supply of this pulsed Nd:YAG laser system. The output pulse was controlled by the microcontroller. The process parameters that have an effect on the adhesion strength of two plastics are determined as the charging voltage, the pulse rate, the beam diameter, and the velocity of the target from many trial-and-error experiments. As a result, the best plastic adhesion strength is obtained from proper values of energy per pulse and peak power. And these values are the energy per pulse of 1.5–1.8 Joule and the peak power of 10–12 kW. Among these, the strongest adhesion intensity without plastic deformation is accomplished when the energy per pulse is 1.64 Joule and the peak power is 10.93 kW. And then, the charging voltage is 650 V and the pulse rate is 11 pps in this case. In addition, it is demonstrated that the optimal beam diameter is 4.00 mm and the optimal velocity of the target is 4.20 mm/s.

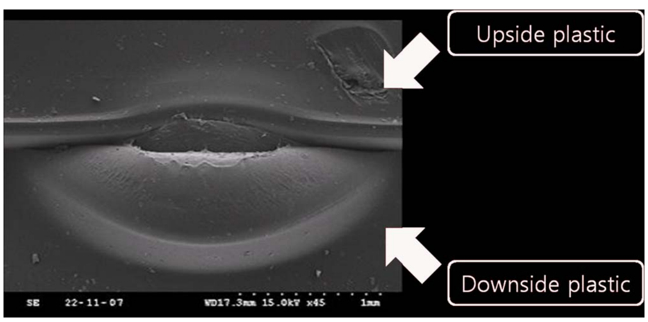

Fig. 12 SEM image of the contact surface.

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