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Cutting Technique for Biodegradable Rope using a CW CO_2 Laser with TEM_{00} mode

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Abstract – A 23 W continuous wavelength CO_2 laser system exited by a high-frequency LCC resonant converter is adapted to cut a biodegradable rope fabricated with polybutylene succinate. As the biodegradable rope consists of three twisted strands, the thickness changes relative to the position of the laser beam and we thus propose a method to determine exact cutting depth. In order to obtain the parameters related to the rope cutting, the experimental and theoretical cutting depths are compared and analyzed for a range of laser heat sources. The melted thickness and groove width of the cut biodegradable rope are also examined. The proposed theoretical cutting depth depends on the incident power and target velocity ratio. From these experimental results, the biodegradable rope with a diameter of 22 mm can be cut with a heat source of 50 J/cm resulting in a melted thickness of 1.96 mm and a groove width of 0.65 mm. The laser system is shown to be perfect tool for the processing of biodegradable rope without the occurrence of raveling.

Keywords: LCC resonant converter, Biodegradable rope, CO_2 laser cutting, PBS

1. Introduction

Lasers are widely used in materials processing and continuous wavelength (CW) CO_2 lasers, in particular, have a wide range of applications such as in ablation and cutting, industrial instrumentation, fabrication of medical equipment, and for dye-sensitized solar cell (DSSC) sealing [1-9].

Polybutylene succinate (PBS) is an aliphatic polymer that typically undergoes biodeterioration via microbes such as *Escherichia coli* and bacteria in the environment, and is thereby converted into residual products such as CO_2 and water. These residual products are environmentally friendly materials, and so, PBS is often used in agriculture, fishing, and medical applications. In the fishing industry especially, biodegradable PBS has recently been used to mitigate ghost fishing caused by gill-net and trap fisheries [10, 11]. Further, process technologies for the manufacture of fishing gear, such as biodegradable ropes and nets, have been actively developed to protect the marine ecosystem by using monofilament and multifilament PBS rope.

Current processing techniques of fishing gear using PBS are generally inadequate for guaranteeing strength. A careful approach to material processing is required because PBS is sensitive to UV radiation and heat. In the fishing industry, rope is usually cut using a heated knife. This requires a lengthy amount of time for heating the knife, and the process is odoriferous. In addition, cutting with an imbalanced hand force can cause the end of the rope to ravel because the cut surface is not uniformly melted by the heated knife.

Laser cutting offers the advantage of uniform cutting. The laser beam irradiates the target evenly ensuring a clean cut and reducing the likelihood of raveling. Employing a CO_2 laser with a long wavelength (10.6 μm) reduces the cutting time because the absorption rate of the CO_2 laser beam is high. Furthermore, the CO_2 laser power can be controlled using the duty ratio or frequency, and material processing is only carried out in the area irradiated the laser beam. This area can also be increased or decreased easily by optical instruments such as the focusing lens or beam extender.

To cut biodegradable rope precise laser power density control is essential [12-14]. Typically, an RF CO_2 laser system is used mainly in material processing because it has been designed for precise laser output power adjustment, has a long lamp life, and superior power control. However, RF CO_2 lasers are expensive, and have a complex structure; they are composed of a π-matching circuit and an RF generator. Also, beam stability for these lasers is not suitable for rope cutting [15].

In this paper, we propose an experimental prototype LCC resonant converter for a 23 W CW CO_2 laser for cutting biodegradable rope. The power output can be adjusted precisely by changing the frequency gain of the resonance tank, and laser is designed with good beam stability. The density and profile of the CO_2 laser beam are simulated using MATLAB® software and this is used for comparisons with the experimental data. We then outline the theoretical cutting depth equation that is related to

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several parameters such as incident power and target velocity. Experimental and theoretical cutting depths are compared for various heat sources and we examine the groove width and strength of the melted thickness.

2. Experiments

2.1 LCC resonant converter circuit design

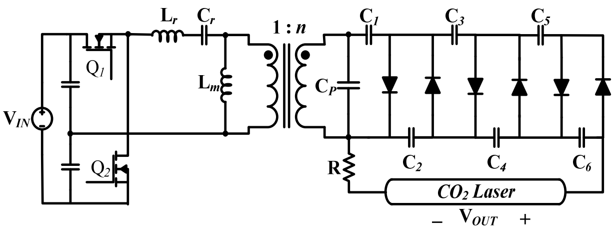

Fig. 1. LCC resonant converter with a three stage Cockcroft-Walton voltage multiplier.

The LCC resonant converter for the CO_2 laser power supply is shown in Fig. 1. It consists of a half-bridge, resonant tank, and three stage Cockcroft-Walton voltage multiplier. The output voltage level of the converter can be adjusted precisely by varying the frequency as the output voltage is controlled by resonant tank gain.

2.2 Power output of the CO_2 laser

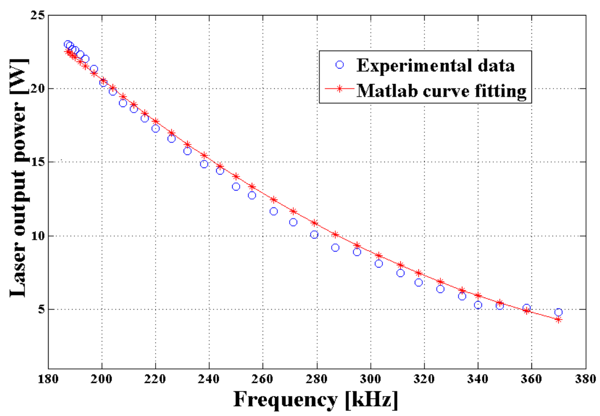

Fig. 2. Experimental data and MATLAB® fitting curve of the laser output power.

Fig. 2 shows a plot of the laser output power versus the operating frequency for the converter. The laser beam power was measured by a power meter (Plus+ 600534), and a function describing the relationship between laser power and frequency was obtained using the MATLAB® curve-fitting tool. The operating frequency ranges between 187.5 kHz and 370 kHz, and the output power is in the range 4.3–23 W.

2.3 CO_2 laser cutting system

A schematic of the CW CO_2 laser system excited by the high frequency LCC resonant converter is shown in Fig. 3. The laser is operated at a wavelength of 10 µm. The optical resonator consists of a totally reflective Mo mirror with a curvature of 10 m, a ZnSe flat mirror with a reflectivity of 90%, and a 450 mm long Pyrex tube with an inner diameter of 19 mm. The discharge length is about 350 mm. An optimized gas mixture of $CO_2/N_2/He$ = 1:9:15 that yields the maximum power is used in the experiments. The laser system is water cooled, and consists of the CO_2 laser, X-Y table, focusing lens and mirror-equipped focusing head.

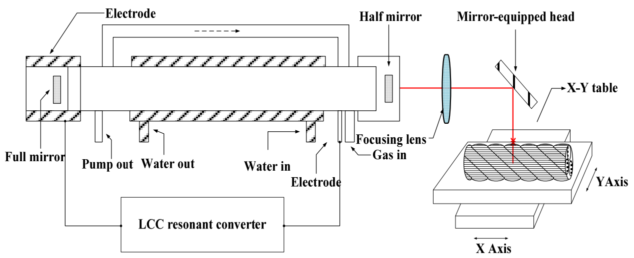

Fig. 3. Configuration of the laser cutting system with the TEM_{00} mode excited by the high frequency LCC resonant converter.

2.4 Proposed depth model and laser beam profiles

During the cutting process, a dynamic energy equilibrium is maintained in the cutting area; the input energy is equal to the output energy. Here, the total input energy (E_t) can be described by the sum of the energy required for cutting (E_q) and the energy lost to heat (E_{loss}) in the surrounding air:

$$E_t = E_q + E_{loss} \tag{1}$$

In the case of cutting a nonmetal target, E_{loss} can be ignored due to high absorption. For the cutting processing, the CO_2 laser beam profile in the TEM_{00} mode can be described as a Gaussian distribution. The laser power density is given by

$$I(x,y) = \frac{\alpha P}{\pi r^2} \exp\left(-\frac{x^2+y^2}{r^2}\right) \tag{2}$$

where α is the absorption coefficient, P is the laser power, r is the beam radius at $1/e^2$, and x and y are the assigned points.

Fig. 4 shows the simulated distribution and laser density profiles of the laser beam using Eq. (2).

The total energy of the laser is the power density integrated over time at the assigned point:

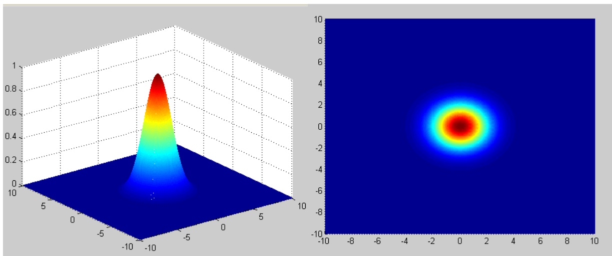

Fig. 4. Gaussian distribution of the laser simulated using Eq. (2).

$$E_t = \int_{-\infty}^{x} \frac{\alpha P}{\pi r^2 v} \exp\left(-\frac{u^2 + y^2}{r^2}\right) du \qquad (3)$$

where v and $dt = du / v$ (u: the moving length) are the mean velocity of the target and the time variation, respectively. The contribution from the y direction can be ignored because the cut is formed at the midpoint of the beam midpoint. Thus, y is set to zero.

The energy required for cutting is given by

$$E_q = \rho D \Delta S [C_p (T_v - T_a) + L_v] \qquad (4)$$

By using Eqs. (1), (2), (3), and (4), the cutting depth can be expressed as

$$D = \frac{\alpha}{\rho\left[C_p (T_v - T_a) + L_v\right] r\sqrt{\pi}} \left(\frac{P}{v}\right) \qquad (5)$$

where ρ is the material density, D is the cutting depth, T_v is the evaporation temperature, T_a is the environment temperature, L_v is the latent heat of vaporization, S is the irradiation area, and C_p is the specific heat of the material.

3. Results and discussion

The biodegradable rope used in the experiment consists of three twisted strands each having a diameter of about 10 mm. The laser beam is focused to the minimum possible diameter (0.63 mm) on the surface. Table 1 lists the properties of the rope.

Table 1. Properties of the biodegradable rope

Properties	Value
Density (ρ)	1.21 g/cm^3
Melting point (T)	155 °C
Rope diameter	22 mm
Specific heat	0.27 J/kg °C

It is typically difficult to measure the cutting depth for rope because the thickness changes relative to the position

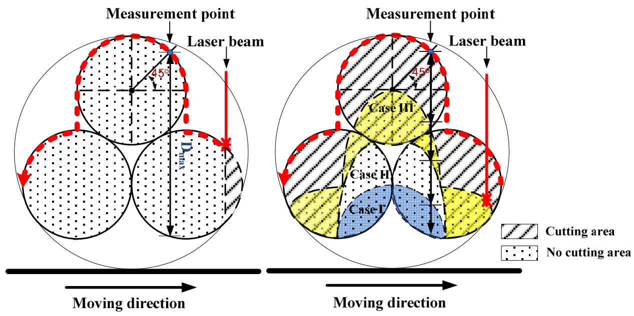

Fig. 5. Measurement scheme for the cutting depth.

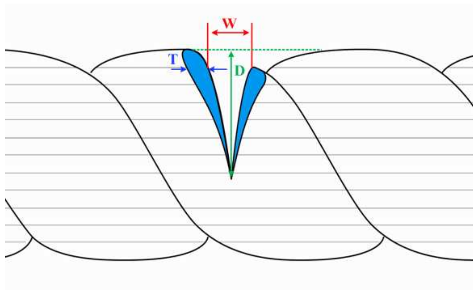

Fig. 6. Geometrical definition of groove width (W), melted thickness (T), and cutting depth (D).

of the laser beam as shown in Fig. 5. The cutting depth can be tracked as cases I, II, and III as the heat source (P_{IN}/v) is decreased. We propose the following method to obtain the exact cutting depth. The measurement is taken from a point that is set at 45 degrees from the horizontal plane of the top strand. A vertical line from this measurement point will give geometrically the maximum cutting depth. Identical experiments to investigate the cutting depth as a function of the heat source are performed, and the depth is measured with a video microscope system (Some TECH, SV-35). The thickness of the melted rope is also measured. Fig. 6 shows geometrical definition of groove width (W), melted thickness (T), and cutting depth (D).

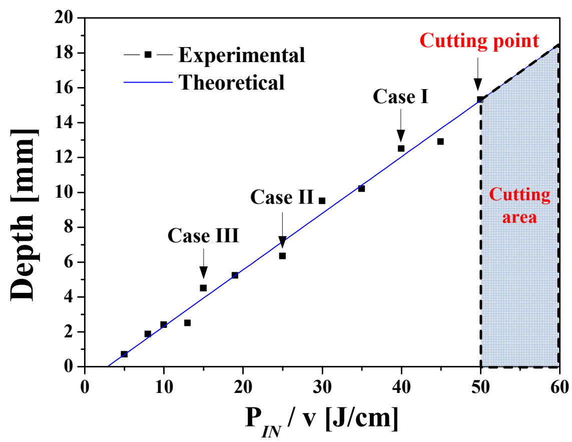

Fig. 7. Comparison of the measured data and theoretical prediction of the cutting depth.

Fig. 7 shows a comparison between the measured and theoretical prediction of the cutting depth as a function of the cutting heat source. The experiments of cutting depth are carried out at a velocity range of 0.3 cm/s to 1 cm/s, and a laser power range of 5W to 23W, respectively.

The biodegradable rope needs to be cut perfectly for a heat source of 50 J/cm; the cutting depth is about 15.3 mm. It means the maximum cutting depth (D_{max}) value, which is distance of between measurement point and bottom as shown in Fig. 5. To cut the rope a larger cutting depth is required and, hence, a larger heat source is required. A larger heat source (over 50 J/cm) will also enable thicker rope to be cut.

Fig. 8 shows a comparison between measured data and theoretical prediction of the groove width as a function of cutting heat source. It reveals that the groove width is not linearly dependent on the cutting heat source. The groove width is the width of the cutting channel; it approaches a value corresponding to the spot diameter r with increasing heat source. An empirical formulation adopted to predict the groove width (W) is given as:

$$W = r\left[1 - \exp\left(-\frac{(P_{IN}/v) - (P_{IN}/v)_{th}}{C}\right)\right] \quad (6)$$

where $(P_{IN}/v)_{th}$ represents the threshold value of the cutting heat source, and C is an experimental constant that correlates the spot diameter r with the cutting heat source (P_{IN}/v) used for the vaporization process.

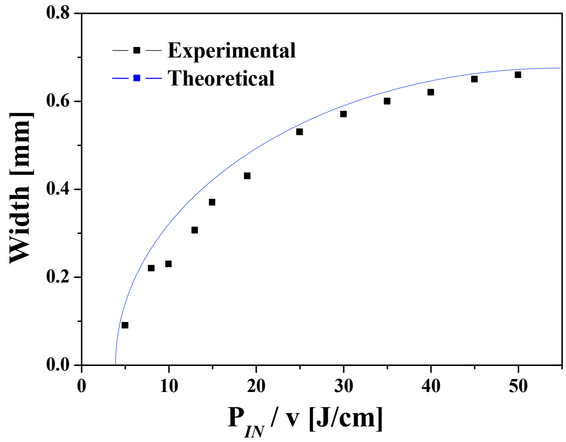

Fig. 8. Comparison of the measured data and theoretical prediction of the groove width.

The experimental results of the melted thickness as a function of cutting heat source are shown in Fig. 9. This graph allows us to estimate length of rope required to compensate for melting.

As shown in Fig. 8 and 9, for a heat source of 45 J/cm, the groove width and melted thickness saturate at 0.65 and 1.96 mm, respectively. Both curves have an exponential relationship with the heat source.

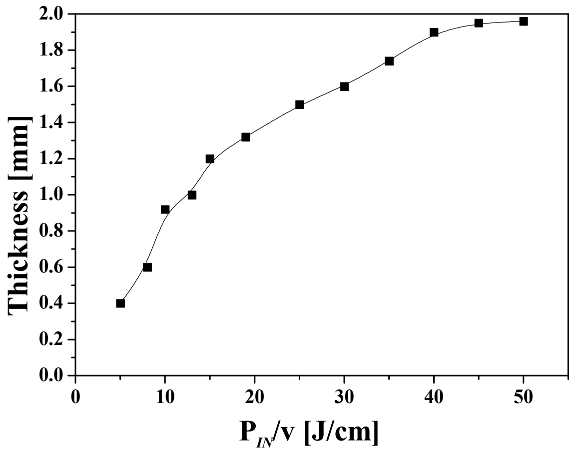

Fig. 9. Experimental results of the melted thickness as a function of cutting heat source.

The finishing process for the cutting surface of the rope is essential for preventing raveling. Thus, we measured the tensile force of the melted surface using a tensile force measuring instrument (INSTRON, Model-4204) in order to ascertain the strength of the cut surface.

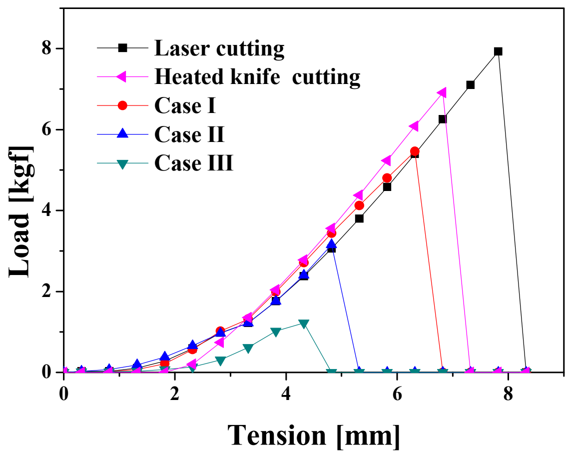

Fig. 10. Comparison of the tensile force for five cases: cutting depths corresponding to case I, II, and III, cutting with a heated knife and laser cut rope.

Fig. 10 shows the tensile force of the melted surface for cutting depths corresponding to case I, II, and III, cutting with a heated knife and perfect laser cutting. The tensile forces are 5.46, 3.15, 1.22, 6.81 and 7.93 kgf, respectively. The conventional cutting method with a knife is heated in 200 – 250 °C when it cut the rope.

From these results, as the cutting depth increases, the tensile force also increases. The tensile force obtained from CO_2 laser cutting is also larger than that of cutting with a heated knife. Thereby, the CO_2 laser cutting method is more effective in preventing rope raveling. The result of laser cut rope is shown in Fig 11. It shows that the photograph of the cross section of melted thickness is cut at heat source of 50 J/cm.

Fig. 11. The cross section of the melted thickness for the biodegradable rope.

4. Conclusion

We have described a 23W CW CO_2 laser system exited by a high-frequency LCC resonant converter that is suitable for biodegradable rope cutting. The experimental results demonstrated performance of the system for rope with a diameter of 22 mm. Measured data was compared to the theoretical prediction of the cutting depth and groove width. Furthermore, the melted thickness and tensile force were investigated ascertain the extent of preventing rope raveling. Both the melted thickness and tensile force of the PBS rope varied as a function of the power to speed ratio of the CO_2 laser. Melting the cut surface prevents possible problems with untied rope. The processing parameters that have the most effect on the rope cutting were determined to be the laser power and target velocity. From the experimental results, the rope can be cut with a heat source of 50 J/cm for the minimum beam size (0.63 mm diameter). Under these conditions, the melted thickness, groove width and tensile force of biodegradable rope were 1.96 mm, 0.65 mm and 7.93 kgf, respectively.

These results will form the basis of further developments to cut rope of various thicknesses. Furthermore, this processing technique has an enormous potential for commercialization.

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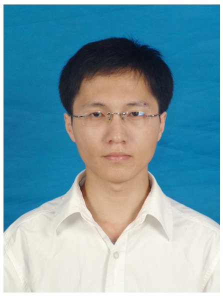

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