Cutting of nonmetallic materials using Nd:YAG laser beam*

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This study deals with Nd:YAG laser cutting nonmetallic materials, which is one of the most important and popular industrial applications of laser. The main theme is to evaluate the effects of Nd:YAG laser beam power besides work piece scanning speed. For approximate cutting depth, a theoretical study is conducted in terms of material property and cutting speed. Results show a nonlinear relation between the cutting depth and input energy. There is no significant effect of speed on cutting depth with the speed being larger than 30 mm/s. An extra energy is utilized in the deep cutting. It is inferred that as the laser power increases, cutting depth increases. The experimental outcomes are in good agreement with theoretical results. This analysis will provide a guideline for laser-based industry to select a suitable laser for cutting, scribing, trimming, engraving, and marking nonmetallic materials.

Keywords: laser power, cutting speed, depth of cut, nonmetallic material, Nd:YAG laser

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1. Introduction

Lasers may be used to cut or shape a wide variety of nonmetallic materials. CO_2 and Nd:YAG lasers have been involved in most cutting operations,[1−4] because they are capable of producing high values of continuous power. The cutting of nonmetallic materials such as paper, plastic, wood, cloth, glass, and rubber can proceed easily in many cases. Because of the higher reflectivity and higher thermal conductivity, cutting of metals generally requires more power.[1] Using a 500-W Nd:YAG laser to cut nylon material seat belts at a cutting speed of 20 mm/s were reported in Refs. [5]–[7]. No burning traces and almost no flaring on the edges were observed during cutting and sealing of nylon. No burring effect was observed when a rubber foam with a thickness of 114 mm was cut by a 275-W Nd:YAG laser, along with a coaxial gas jet and a lens of 254-mm focal length at a speed of 16.6 mm/s. Peters[8] inspected the performance of a low power (1 kW) CO_2-laser in wood cutting, and pointed out that the water content affected appreciably the cutting speed of wood. Nuss[9] exercised a low power (1 kW) Nd:YAG laser in cutting parts of a toughened plastics mould and compared the results with those from other important techniques which are regularly used in cutting. From this comparison it follows that no technique can match a laser cutting method in the sense of cutting speed, cleanliness, and time utilization on post operation work. Zhou *et al.*[6] and John[11] studied some hard ceramics material cuttings. In order to cut the ceramic materials with thicknesses ranging from 0.6 mm to 4 mm at a cutting speed of up to 20 mm/s, a 1500-W laser was used. In addition, Todd[12] mentioned that Nd:YAG laser beam of 560-W power is sufficient to cut ceramic materials at a speed of 5.3 mm/s. Also some other researchers reported on nonmetallic material cutting in which high power lasers are used to cut plastic sheets with small thicknesses in a range of even 5 mm–25 mm. From this, a question arises why the low-power lasers are not utilized. A few reports are also found in the liter-

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ature related to the applications of low power lasers, in which the nonmetallic material cutting by low power CO_2 laser was analysed.[5] However, to the best of the authors' knowledge, studies about the Nd:YAG laser can provide an opportunity to find out the speed and laser beam intensity for presetting marking depths for different materials and have been hardly reported.

The purpose of this study is to investigate the applications of low power Nd:YAG lasers. In this work we also report on theoretical experimental investigations of the dependence of approximate cutting depth on cutting speed and laser power for different materials.

2. Theoretical modeling

Various theoretical models[13−15] have been developed for laser machining. The lasers employed for cutting purposes in industry are usually in "transverse electromagnetic mode" (TEM00). The TEM00 is a painstaking mode for cutting because of minimum diffraction effects, focused spot size in small area, etc. In this mode, most of the energy is focused in an area of small radius, and laser beam intensity is described by a "Gaussian energy distribution". The equation used for cutting depth (D) for TEM00 as mentioned in detail in Refs. [5] and [16] is

$$D = \frac{aPR\sqrt{\pi}}{\pi R^2 VQ\rho} = \frac{a}{QR\rho\sqrt{\pi}}\left(\frac{P}{V}\right), \qquad (1)$$

where P is the output power of the laser beam having energy absorptivity a, V is the uniform workpiece moving speed when the laser beam falls on it, R is the laser beam radius, Q(J/g) is the specific heat energy of the material, and ρ is the density of the material.

Equation (1) shows that the cut depth is linear to the power of laser and nonlinear to the cutting speed. Because of high absorptive power of nonmetallic materials for Nd:YAG laser at 1064-nm wavelength, it is assumed that the material can absorb all of the laser energy and the energy is converted into heat that ultimately vaporizes the material. Energy lost to the surroundings is ignored using the energy balance method. The depth of cut D (along the y axis) versus the laser speed V (along the x axis) are plotted in Fig. 1. In the cutting case we used the Acrylic plastic material whose density and specific heat are 1.18×10^{-3} g/mm^3 and 2 kJ/g respectively. The value of material absorption coefficient, a, is assumed to be 1, i.e. $a = 1$. The "focused laser beam" has radius $r = 0.25$ mm and output powers of 20, 40, and 80 W separately.

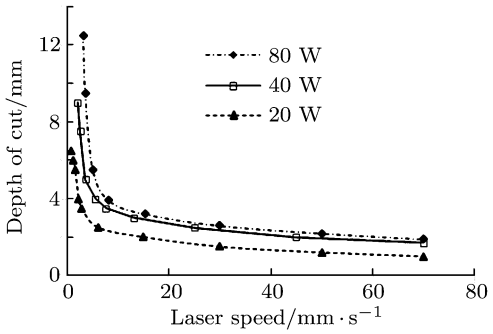


Fig. 1. Theoretical variations of laser depth of cut with the laser speed for different laser powers.

3. Materials and method

Nd:YAG laser has undoubtedly been considered to be the most important technical development since the Ruby laser was discovered in 1961. Nd:YAG lasers of less than 100-W power output are most frequently used. The Nd:YAG laser wavelength is 1064 nm and falls in a range of infrared radiation which is also referred to as thermal radiation. Different power levels of Nd:YAG laser and workpiece cutting speeds are used for cutting various materials in our work. In the experimental laser cutting process, the laser head is fixed whereas the workpiece moves underneath the laser beam positioned on a table as shown in Fig. 2.

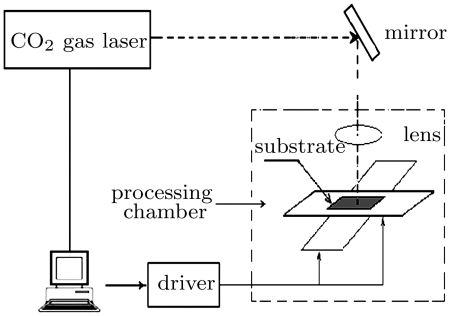


Fig. 2. Configuration of laser cutting system with single beam.

To control work-table movement along the x direction and the y direction, a personal computer (PC) is used. Since the processing cabinet forms a closed system, when the laser is working, the operation of the laser can be recorded by a camera installed inside the system and then displayed on a monitor. The

laser head has a high stability and a robust monolithic structure and it is mounted on the top of the processing chamber. A diode laser is used to align the infrared laser beam. An optic lens set is used to deliver a focused laser beam of wavelength = 1.064 μm, laser power = 100 W, and beam diameter = 7 mm on the surface of the workpiece. A mirror in the set reflects the laser beam in the z-axis (downward) direction perpendicular to the workpiece x–y plane focusing a beam of radius 'R' by a lens with a focal length of 70 mm. At the centre of this focused radius 'R', the maximum depth of cut is obtained. This indicates that the maximum depth of cut appearing at the centre is due to the central line of beam falling on the workpiece surface. For this reason only energy distributed along the central line of beam is taken into account. The laser intensity and the cutting speed used in this experiment range from 10 W to 80 W and from 0.2 mm/s to 300 mm/s respectively.

4. Results and discussion

The most important factor in the field of laser processing is laser cutting quality. Therefore the current work mainly focuses on cutting parameters (like cutting speed, laser power, workpiece thickness, and assisting gas pressure) to understand the relationships between above said parameters and resulting cutting quality. In this work, the cutting of plastic board, pinewood, rubber, and glass materials is performed using the laser at different power levels. Most of the above mentioned materials show nearly the same trends in the laser cutting.

A focused beam of Nd:YAG laser with radius 0.25 mm is used to cut plastic material having a density of 1.18 g/cm^3 and specific heat energy of 5 kJ/g. Variation in cut depth is investigated by using the laser at different powers and cutting speeds. The outcomes of this study are plotted in Fig. 3.

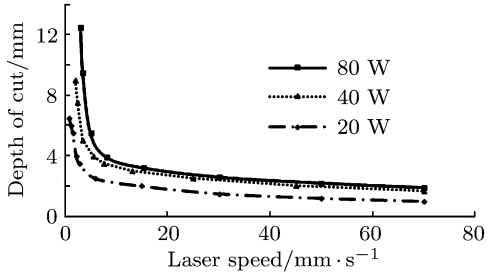


Fig. 3. Variations of laser depth of cut with the laser speed for different laser powers.

Experimental results in Fig. 3 reveal that there is no significant effect of speed change observed on cutting depth after 30 mm/s and the change in depth is not linear with speed either. A linear relation is found between laser power and cutting depth. During laser cutting, melting and evaporation of the material take place, this must slightly reduce the width of cut, therefore the laser intensity will go on decreasing, owing to the blocking effect of evaporated/melted materials because the role of this effect becomes more evident within a deep cut. Additionally the blocking effect is also influenced by material properties. When the cut depth is very deep and workpiece speed is low, this effect reduces the effectiveness that the cut depth increases with laser power increasing.

Beside this, further experiments are performed for other nonmetallic materials such as pinewood, particleboard, rubber, etc. in the same way as in the case of plastic. For other nonmetallic materials, variation in cut depth with laser speed approximately exhibits a similar trend to that in the case of plastic. Experimental laser cutting results for these materials produced at 80-W powers are shown in Fig. 4.

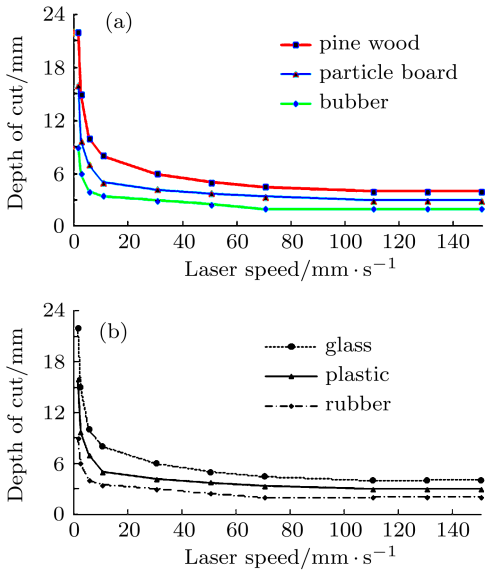


Fig. 4. (colour online) Experimental cutting results for pinewood, particle board, and rubber at 80-W laser power.

As for wood, it is noticed that laser cutting results are badly affected by water content inside wood. To minimize the water effect, dry samples of pine are used in our experiment. It is observed that variation in depth of cut occurs before the workpiece moving speed is less than 100 mm/s but when workpiece moving speed reaches 110 m/s, its effect almost becomes

negligible and cutting depth does not change. Figure 4 illustrates clearly that the cutting depth of rubber is lower than those of other materials at a speed less than 30 mm/s because during rubber cutting smoke production is more in comparison with that during cutting other materials. The produced smoke absorbs a part of laser energy, which ultimately reduces the intensity of laser beam. It should be further noted particularly in the case of plastic that when cutting depth is more than 40 mm, a more powerful laser beam is required.

Theoretical analysis has given great confidence to our understanding of the process mechanism, thereby making laser processing more acceptable as an established and reliable processing method. Theoretical predictions as mentioned above are shown in Fig. 1 and matched with the experimental results that are plotted in Figs. 3 and 4. At low laser speed, a significant discrepancy in cutting depth is noted. This discrepancy may be attributed mainly to the fact that some blocking factors of material and other material property such as heat conduction are not included in theoretical analysis. The laser power is also overestimated for depth of cut from Eq. (1).

In this study we established the low power Nd:YAG laser cutting for nonmetallic materials. This laser is appropriate specifically in plastic cutting because of much higher "absorptivity" for Nd:YAG laser. Besides an excellent tool of cutting, some toxic gases are produced in this process. The cutting speed should be kept low otherwise kerfs can char, in particular, in the cutting of particleboard and wood. For rubber cutting Nd:YAG laser quality is also good if there is any arrangement to disperse vaporized material.

5. Conclusion

Based on the theoretical predictions and experimental results it is concluded that the cutting of nonmetallic materials can be performed by a low power Nd:YAG laser. It is observed that for all materials, cutting depth does not increase linearly with the increase of laser input power. For deep cutting a laser of an extra power is required.

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References

[1] John F R 1999 *Industrial Application of Lasers* (New York: Academic Press) pp. 404–415

[2] Stournaras A, Stavropoulos P, Salonitis K, Chryssolouris G and Stournaras A 2009 *CIRP J. Manufac. Sci. Tech.* **2** 61

[3] Davima J P, Barricasa N, Conceicao M and Oliveirab C 2008 *J. Mater. Process. Tech.* **198** 99

[4] Choudhury I A and Shirley S 2010 *Optics & Laser Technology* **42** 503

[5] Pfeifer R, Herzog D, Hustedt M and Barcikowski S 2010 *J. Mater. Process. Tech.* **210** 1918

[6] Zhou B H and Mahdavian S M 2004 *J. Mater. Process. Tech.* **128** 188

[7] Yilba B S 1996 *J. Mater. Process. Tech.* **58** 323

[8] Coherent Inc. Saunders R 1980 *Laser-operation, Equipment, Application and Design* ed. Bellis J (New York: McGraw-Hill) pp.137–196

[9] Peters C C 1975 *USDA Forest Service Paper FPL* **250** 346

[10] Nuss R 1988 *Proceedings of the 5th International Conference on Laser in Manufacturing*, September 13–14, 1988 Stuttgart, West Germany, p. 340

[11] Mayfield J H 1978 *Am. Mach.* **11** 18

[12] Todd J A 1997 *J. Manuf. Sci. Eng.* **119** 155

[13] Vicannk M G, Simon H M and Recker I 1987 *J. Phys.* **20**

[14] Cai L and Sheng P 1996 *J. Manuf. Sci. Eng.* **118** 225

[15] Pietro D P and Yao Y L 1995 *Int. J. Mach. Tools Manuf.* **35** 673

[16] Zhou B H 1999 "Application of Laser Marking and Cutting of Materials in Manufacturing Industry" *Master Thesis* (Melbourne Australia: RMIT University)