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High-power Yb-doped Fibre Laser for Cutting Dry Pine Wood

Juan Carlos Hernandez*, Philippus Crouse, Lin Li

Abstract— **This article reports experiments on the laser wood-cutting performance of a 1 kW ytterbium fibre laser - a recent, compact, flexible, efficient laser system. The cutting process is characterized, taking as a reference the effects of the principal process factors. A quantification of energy consumption during the cutting process, critical for scale-up, is provided.**

Index Terms— **Laser cutting, wood, Yb-doped fibre laser.**

I. INTRODUCTION

The laser cutting of dry wood was one of the first applications of industrial laser cutting systems early in the 1970s when a CO_2 laser beam was used for cutting die boards for the packing industry [1], [2]. Nowadays laser systems continue to be used in this application because of the advantage of their capability to cut complicated patterns. They have also found their place in the furniture industry where it is possible to obtain a fully automated cutting process allowing, for instance, the cutting of wood inlays [3]. Moreover, the darkened cut surfaces obtained from the laser cut sometimes actually provide a decorative effect to the cut surface [2], [4]. Other advantages of laser cutting of wood in comparison with conventional cutting methods include: highly precise cuts; absence of mechanical stress in the work piece; no tool wear; low noise emission; narrow kerf width; reduced amount of sawdust; and extremely smooth surfaces [4]-[15]. However, laser cutting in comparison with sawing does have the disadvantage of lower feed rates. When cutting wood with a laser beam, a fine layer of charred material is left on the cut surface as a result of the thermal process [3], [6], [16]-[18]. The charring of laser-cut surfaces cannot be avoided for wood thickness of more than 6 mm [8]. Previous papers on laser wood cutting with a CO_2 laser beam were dedicated to investigating the principal parameters involved in the process. These are: power level; feed rate; the focal spot size and its position along the thickness; and the use of different assist gases at various pressures [5], [6], [12]. The density and moisture content of wood are commonly related to the cut process. Both affect power consumption, and thus play an important role in the productivity of the separation process [5], [6], [19].

The CO_2 laser has also been tested for cutting green wood. Explorations in this field include the cutting of green wood boards [6] as well as branches [20]. These results confirmed the feasibility of cutting dry and green wood with laser beams. The CO_2 laser is currently the most widely used laser in cutting operations of wood; however its beam quality is not the best available in the market of high power laser systems. The same is true regarding its energy transformation efficiency. Other disadvantages of the CO_2 laser are the rigidity of its beam-guiding and focussing elements as well as the large volume of the complete system.

Other laser systems have been used in wood cutting experiments. A femtosecond Ti-sapphire produced a superior cut surface and displayed no cell damage or charring [11]. The very short time interaction between laser and material is the reason for these characteristics [11]. However, their low average power output eliminates these lasers as practical systems for this application.

Given the present limitations of the CO_2 and femtosecond lasers, one possible solution is to employ a high-power fibre laser. Fibre lasers are attractive because their geometry allows for more simple thermal management than conventional solid-state lasers. The heat generated can be dissipated over a long length of fibre, which minimizes the risk of damage. In addition, the output beam quality is determined by the wave guiding properties of the active-ion doped core, which can be easily managed to produce a single spatial mode. Fibre lasers have output powers comparable with Nd:YAG systems, while exhibiting superior beam quality [21], [22]. The output powers of the fibre lasers are close to those obtained with CO_2 lasers [21], but the beam quality is superior. These favourable characteristics of the fibre laser open the possibility of exploring laser cutting of wood and other organic materials which are located at large distances from the laser source. Under field conditions, for example, it could be applied to cutting trees and grass. The rapid development of laser technology allows the anticipation of this application which, if technically possible, would result in a precise, efficient cutting operation with a considerable reduction of wasted materials. This operation would help to reduce the consumption of fossil fuels in tree cutting and grass cutting. Moreover, using lasers to cut grass would make it possible to reach corners and other difficult access points. However, using a laser beam as a cutting tool demands the application of appropriate safety measures, especially if it is intended to be used in outdoor conditions. As a first step in the direction of practical application, this paper explores the feasibility of cutting dry pine wood with a high-power ytterbium fibre laser. The aim of this study is to obtain initial information about the wood

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Laser Processing Research Centre, Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester. P.O. Box 88, Manchester M60 1QD, UK

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*Corresponding author: Telephone: +44 161 306 2370; Fax: +44 161 306 3803; e-mail: Juan.Hernandez-castaneda@postgrad.manchester.ac.uk

cutting process with this recent laser source. We are interested in finding the cutting rates and the kerf characteristics as a function of process parameters, and importantly, energy consumption.

II. EXPERIMENTAL

A. *Experimental apparatus*

In all these experiments an Ytterbium-doped fibre laser (see Figure 1) was used. Technical details of the system are as follows:

- Model: IPG GmbH, single mode YLR-1000-SM
- Power: 0 – 1 kW (CW)
- Wavelength: 1070-1080 nm
- M^2: 1.1-1.2
- Beam delivery: optical fibre, 14 μm core diameter

The laser unit is integrated with a CNC X-Y table, which controls the movement of the work-piece under the stationary cutting head. The laser beam displays a TEM_{00} mode, and it is focused with a ZnSe lens of Ø 38.1 mm (1.5 in) with focal length of 127 mm (5 in). A coaxial gas jet is delivered along with the laser beam, in our case compressed air.

Figure 1. YLR-1000-SM Ytterbium-doped fibre laser system employed with the cutting set up.

B. *Material properties*

Wood is a heterogeneous and anisotropic material, whose properties are highly variable according to its natural formation inside the tree. The variation of wood properties begins with the type of tree, *i.e.* either “softwood” (conifers) or “hardwood” (broad leaved trees) [24], [25]. Because they grow under different site conditions, there is also wide variation in the properties and characteristics of wood obtained from trees of the same species. There is even more evident variation of wood properties obtained from trees of different species.

In these experiments we used dry pine wood, which is classified as softwood, because it is readily available, and because of its more homogeneous properties. Commercial dry pine wood strips of 25.4 mm x 25.4 mm (1 in^2) cross section were used in the laser cutting experiments. The density and moisture content of the wood samples were measured, as previous research [5], [6], [12], [19] signalled these properties as the most relevant to the laser cutting process. In order to relate the cutting results obtained to the values of these wood properties, the mass removal rate is calculated and energy consumption is estimated using the value of density.

Wood density is usually determined at zero moisture content, which is called the oven dry density [24]-[26]. We measured the density of the samples by weighting the dry mass of the wood samples with a scale (accuracy ten milligrams), and measuring its dry cubic volume with a micrometer. The recorded oven dry density of the samples gave a mean value of 0.4949 g/cm^3.

The moisture content of these samples was determined by the oven dry method. It consists of obtaining the mass of water in the sample, which is divided by the dry mass of the sample, and the result is expressed as a percentage. The mean measured moisture content of our wood samples was 8.95 %.

The samples of dry wood were cut to 8 cm length and they were fixed to the X-Y table for the laser cutting process. The laser beam was delivered with a spot diameter of 100 μm at the top surface of the samples. In this experiment we combined four cutting velocities (10, 20, 30, and 40 mm/s) with four power levels (250, 500, 750, and 1000 W), which resulted in 16 cutting treatments. The experimental set was performed at four different air gas pressures, 2, 3, 4, and 5 bar. The samples were cut perpendicular to the grain direction, which corresponds to transversally cutting the structural elements of the tree’s trunk and branches. These elements are the tracheids in softwoods, and fibres and vessels in hardwoods species [24]-[26]. The cutting operation was also performed in the radial direction, taking the transversal section of the trunk as reference. The complete treatment was repeated for the validation of the results obtained. The mass removed in each run was also recorded to validate the mass removal values obtained from volume of kerf and wood density. All cutting tracks (length of 25.4 mm) were sectioned in four parts for the measurement of the transverse cut section obtained. The profiles were pictured digitally and the measurements of the kerf section area, width and depth were performed with digital image manipulation software.

III. RESULTS AND DISCUSSION

The first observation about the process is that the laser cutting track is not homogeneous, as less material is removed when the laser beam passes through the growth rings of the wood (see Figure 2). The cutting profile width and depth reduce when the laser meets the "late wood" (wood produced in the fall) section of the growth ring. This effect has been reported in previous works on laser wood cutting by CO_2 laser [8], [16], [27]. This phenomenon is explained by the fact that "early wood", which is the wood generated in spring, is less dense than "late wood". Early wood, generally of clearer colour, is formed by larger cells with thin walls, whereas late wood of darker colour has smaller cells with thicker cell walls [24], [25].

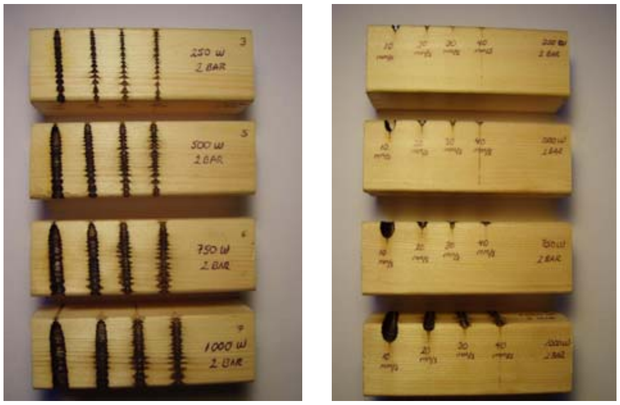
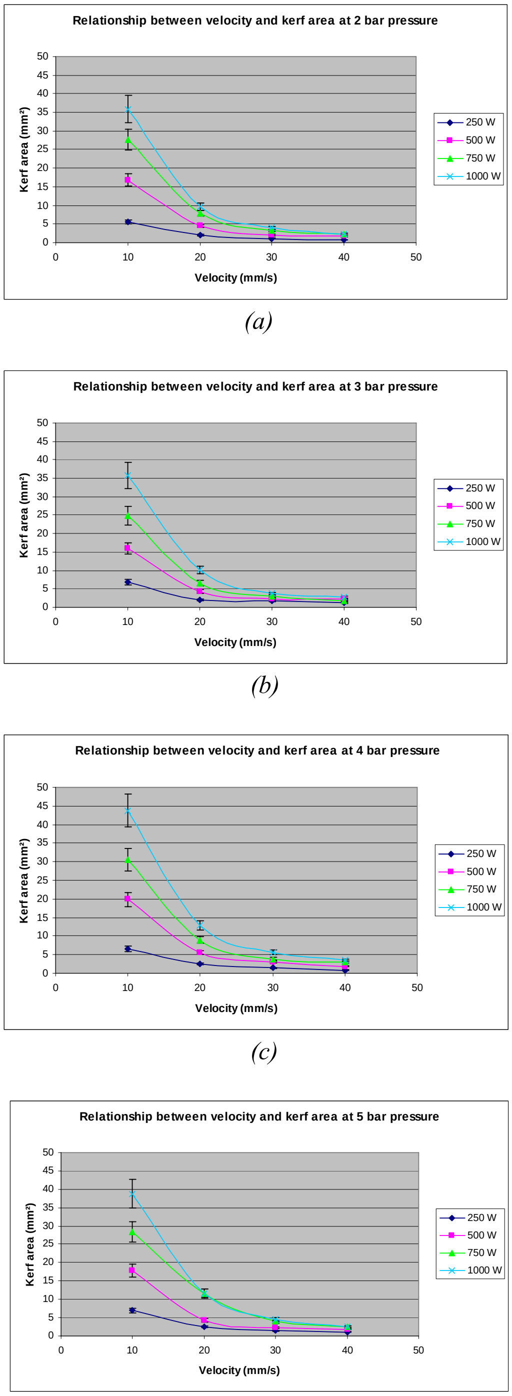


Figure 2. Top and side view of the samples cut by fibre laser beam in the radial direction.

Another noticeable aspect is the charring of the cutting track as a result of the thermal action of the laser beam. From Figure 2 it is also clear that the broad cutting kerf display a rounded profile. Finally, as is expected, the cut sections became wider and deeper with an increase of the power applied, and also with the reduction of the cut velocity. The largest kerfs obtained correspond to the combination of high powers and low velocities. This phenomenon is obviously related to the total amount of energy delivered to the wood sample.

In Figures 3(a), 3(b), 3(c) & 3(d) the effects of laser power, cutting speed, and gas pressure on the cross-sectional area of the kerf are illustrated graphically. The higher the laser power, the larger is the area of the cut section. At lower cutting speed, the profile area of the cut increases, because of increased interaction time of the laser beam with the sample. In this figure it is also possible to appreciate how the increase of air pressure favours the broadening of the cutting kerf. Similar behaviour is shown by the kerf depth in Figures 4(a), 4(b), 4(c) and 4(d). Here the effect of air pressure and cutting velocity at constant power for each graph is used. In the case of 250 W, 500 W, and 750 W the increase in air pressure produces deeper and wider sections. However for the 1000 W power, the effect of air pressure is considerably reduced (see Figure 4d), undoubtedly because at this high power, the percentage contribution of the enthalpy of combustion is less significant.



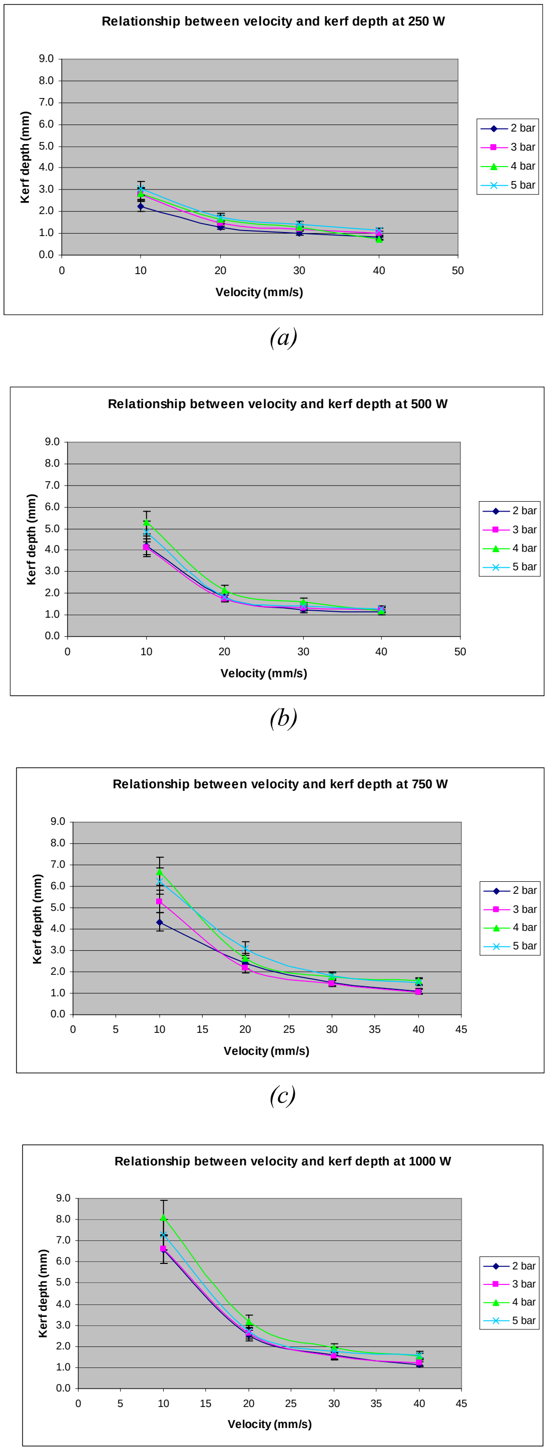
(a)

(b)

(c)

(d)

Figure 3. The kerf area obtained at different combinations of velocities and output powers, at the four air pressures used.



(a)

(b)

(c)

(d)

Figure 4. The effect of cutting velocity and air pressures on kerf depth at constant output power.

Equation (1) below is used to estimate the energy consumption during the fibre laser cutting process of dry wood.

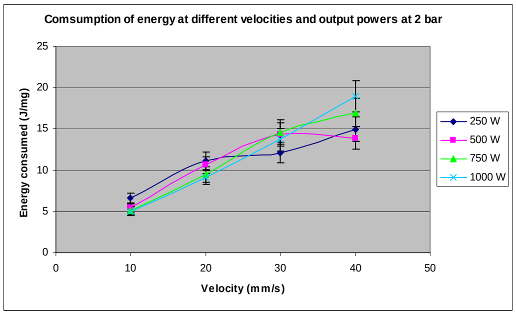
$$CE = \frac{P \times \tau}{\Delta m} \qquad (1)$$

where *CE* is the consumed energy (J/mg), *P* the laser power (W), τ the interaction time (s), and *Δm* the removed mass (mg). The interaction time (τ) is calculated by dividing the cutting length by the velocity. On the other hand the mass removed (Δ*m*) is obtained by multiplying the kerf area by the cutting length and the density of the material. Thus the consumed energy is directly obtained by

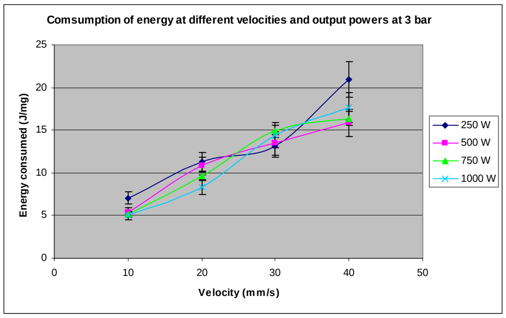
$$CE = \frac{P}{v \times A \times \rho} \qquad (2)$$

where *v* is the cutting velocity, *A* is the kerf area, and ρ is the wood density. Applying equation (2) to all the parameters combinations, we obtain the consumed laser energy used in the removal of the material from the cutting kerf (J/mg). All treatments tested resulted in an average consumed energy of 10.75 J/mg.

Figures 5(a) to 5(d) show the laser energy consumed in the removal of materials from the kerf for all the combinations of power and velocity explored at the four air pressures tested. As one would expect, at low air pressures the process is less efficient than it is at higher air pressures. This makes sense if one considers that the energy generated by the combustion of wood contributes to the energy balance of the cutting process. At low flow rates the combustion reduces and the energy to perform the cutting is mainly supplied by the laser beam, making the process less efficient. On the other hand with high flow rates the combustion of wood improves and the input energy of the laser beam reduces, making the process more efficient (see Figures 5c and 5d). The high flow rates and sufficient oxygen availability provided by 4 & 5 bar, the effect on efficiency by the other parameters is much less marked. Specific energy values of 10 kJ.g^{-1} (3 kWh.kg^{-1}) are demonstrated.



(a)



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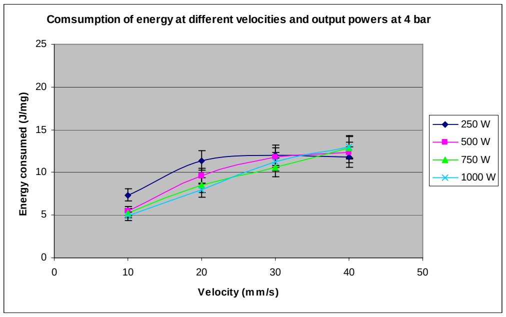
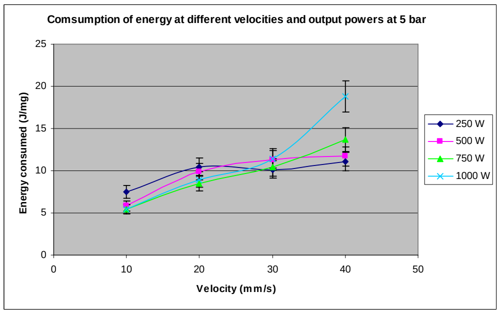


(c)



(d)

Figure 5. The laser energy consumed in the mass removal from the cutting kerf at each air pressure tested.

IV. CONCLUSIONS

From our experimental results we have established the feasibility of cutting dry wood with a high power fibre laser. The kerf profiles obtained at the tested combinations of process parameters were round and their roundness factor was higher than 0.55 for the entire set of experiments.

The laser wood cutting process with an ytterbium fibre laser shows a fine layer of charred material on the cut surfaces, the product of the thermal process involved. The cut profile (along the cutting track) showed irregularities when the laser beam encountered the late wood section of the rings of growth. A reduction in the depth and width of the kerf was observed because of the higher density of the late wood.

An increase in the kerf area, and therefore an increase in the volume of the removed material, was obtained when high powers and lower velocities were applied. This is because of the higher energy delivered and the larger interaction time between the laser beam and the material. The opposite result is true for the combination of low powers and high velocities.

An increase in the pressure of the assist gas jet improved combustion and helped augment the mass removal of the material, which made the process more efficient when compared with lower gas jet pressures.

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