Factors influencing laser cutting of wood

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Abstract

Factors influencing the ability of lasers to cut wood may be generally classified into these three areas: 1) characteristics of the laser beam; 2) equipment and processing variables; and 3) properties of the workpiece. Effects of beam power, mode, polarization, and stability are discussed as are aspects of optics, location of focal point, feed speed, gas-jet assist system and workpiece thickness, density, and moisture content.

Newly designed continuous wave carbon dioxide lasers with powers in excess of 1 kW are rapidly being applied to cut, weld, and heat-treat metals. Several thousand units are in place, many working alongside conventional machine tools in normal production environments. They have proven stable, reliable, and cost effective. While all hard maple steel rule die blocks used for cutting and creasing paper cartons are machined with laser profilers, the secondary wood processing industry has been slow to apply this new technology.

Yet, as laser manufacturers and wood industry managers become more familiar with the materials processing potential of lasers, it is likely that many more important applications will be developed. Central to the problem is a more complete understanding of the complex interactions between the laser beam and wood. These can be grouped into three major areas: 1) characteristics of the laser beam; 2) equipment and processing variables; and 3) properties of the work material. Important beam characteristics include power, mode, polarization, and stability. Significant equipment and processing variables involve the design of the beam delivery optics, location of the focal point, feed speed, design of the gas-jet assist system, type of gas used, and gas pressure. Factors related to the workpiece include thickness, density, moisture content, extractives, and the basic optical properties of wood. For composite wood products, the quantity and type of adhesives and presence of additives such as wax are also important as are the shape and orientation of the particulate elements.

This paper summarizes the effect of these factors on the ability of lasers to cut wood.

Beam characteristics

Industrial carbon dioxide lasers for wood cutting and engraving are available in a range of output powers from less than 100 W to several thousand kilowatts. Within this range, beam penetration is greater and thicker wood can be cut with increasing power. Also, for a given thickness, faster cutting speeds can be achieved. Since the cost of a laser is proportional to output power, the power level must be carefully selected based on the cutting speed requirements and by the thickness and other properties of the material.

Several authors have developed equations relating power to feed speed and to depth of cut (3, 7, 11). However, there is no information on the interactions of power and other factors (i.e., wood density, location of the focal point, focal length, etc.) needed to more completely describe the laser cutting process in mathematical terms useful in industrial applications.

At present, most lasers for cutting wood have powers ranging from 200 to 800 W and are used to manufacture a few specialty items for furniture (5). Additional research is needed to determine the interactive effects of power for a greater range of applications using lasers having powers between 1 to 5 kW.

The transverse electromagnetic mode (TEM) structure of a laser determines the distribution of beam energy in three-dimensional space (Fig. 1). It is the quality of the beam profile rather than total power that

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determines ultimate processing performance. Most lasers for cutting are designed to generate a Gaussian or near-Gaussian energy distribution (TEM_{00}). This type of beam can form a small focal point and generate the high energy density needed for cutting. Additionally, the energy profile is the same about all axes; this characteristic is important where cutting performance must be independent of direction (Fig. 2). Because the Gaussian energy distribution exhibits a sharp peak, the energy density at the center of the focused beam is significantly higher than the average energy. With a multimode beam of equal output power to a TEM_{00} beam, the power density at the focal point may be as much as two orders of magnitude less. The single versus multimodal effect is analogous to cutting with a sharp versus a blunt tool.

Polarization is associated with the electrical and magnetic field components of laser light. In metal cutting, polarization affects the absorption of laser energy and hence cutting speed and cut surface quality. The effects of polarization in cutting wood are not known. However, it is possible that polarization could be used to alter the shape of the beam to improve the smoothness of cut surfaces or yield cuts having a contoured or shaped surface similar to those obtained with conventional routers, shapers, or molders.

Lastly, uniform material processing requires a laser with a stable and predictable power output over lengthy periods of time. Power instabilities can result from fundamental sources related to the laser process itself or from factors related to system design and implementation.

Equipment and processing factors

The design and type of optics determine the geometry and energy concentration of the focused laser light rays. Figure 3 illustrates a typical beam delivery system. In this design, the system "floats" the beam focusing and gas-jet delivery assembly at a fixed distance above the workpiece to compensate for irregularities in surface flatness.

For wood cutting, the beam is usually focused with a single lens. The effect of focal length on spot size within the focal zone and thus power density is illustrated in Figure 4. The figure shows that a lens with a long focal length (FL) forms a larger diameter spot (AR) in the focal zone (DF) but the beam is concentrated over a greater distance, i.e., the depth of focus is greater for a lens with a long focal length than for one with a shorter length. The angle θ (divergence angle), in combination with the wavelength of the laser light and focal length, also influences the depth of focus and minimum spot size in the focal zone. The power density is a function of this cross-sectional area and the laser output power. Lasers used for cutting typically achieve power densities at the focal point in the order of 10^6 to 10^8 W/cm^2.

An optics system with a long focal length is needed to obtain a relatively uniform power density, particularly when cutting thick material. Focal lengths from 75 to 150 mm have been shown to yield satisfactory results when cutting wood, particleboards, and fiberboards (7, 10). However, there is no information

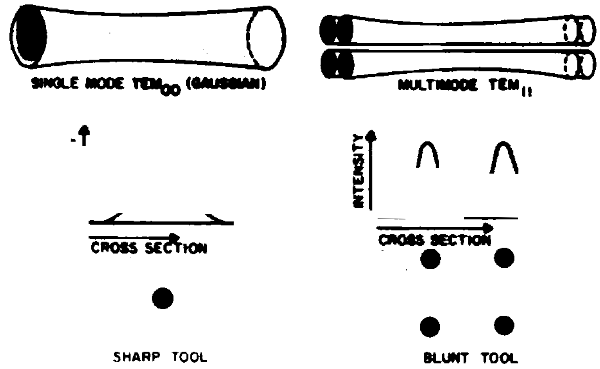

Figure 1. — Two types of transverse beam modes (adapted from (12)).

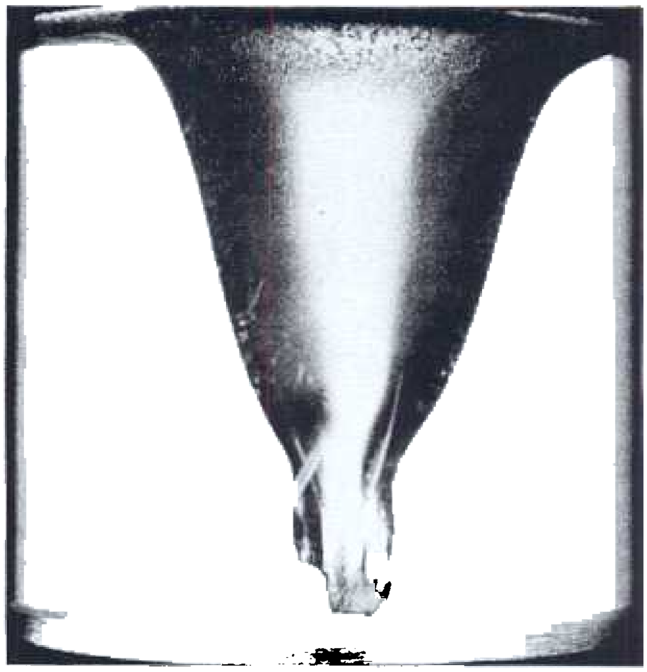

Figure 2. — Burn impression in Plexiglas of an unfocused 1-kW laser beam with Gaussian energy distribution.

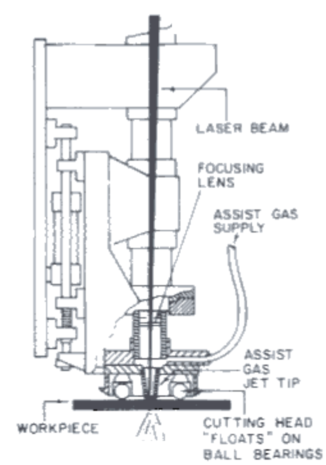

Figure 3. Typical beam delivery system for cutting wood (adapted from (1)).

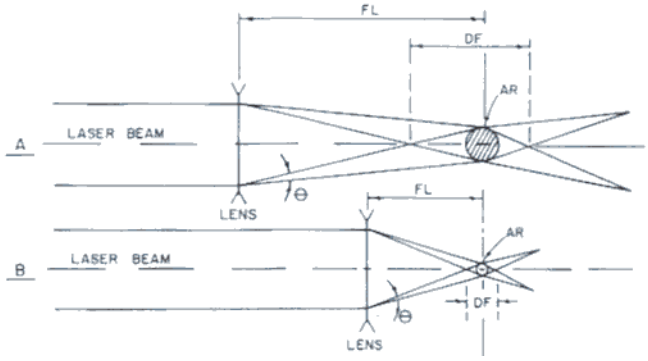

Figure 4. — Optical relationships within a focused laser beam: AR = The area of maximum energy and minimum cross section; DF = Depth of focus in focal zone; FL = Focal length; θ = Divergence angle.

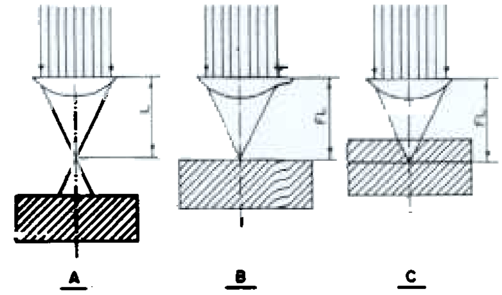

Figure 5. — Possible locations of the focal point relative to the workpiece. Distance FL is the focal length.

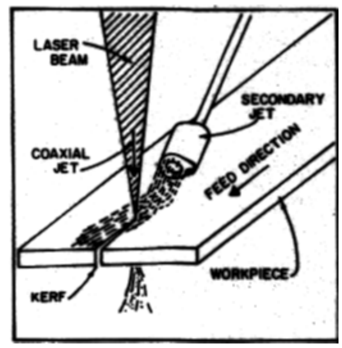

Figure 6. — Auxiliary off-axis jet assist.

defining the optimum focal length when cutting wood greater than 2 inches thick.

The location of the focal point with respect to the workpiece also affects cutting efficiency. Figure 5 illustrates possible locations. If the focal point is above the work surface (Fig. 5A), the energy density is diminished, kerf width is increased, and the upper surface of the work may be charred. If the focal point is located as in Figure 5B, maximum energy is at the surface but diminishes as the thickness of the workpiece increases. If the focal point is positioned at or slightly above the middle of the workpiece (Fig. 5C), the energy density is more uniform throughout the thickness. In the latter case, kerf width is smaller and more uniform, the cut surface has less char and is smoother, and deeper cuts are possible. When cutting thin material, the position of the focal point is not as critical. The location of the focal point is particularly critical for cuts to inlay metal or wood strips where the width and depth of the cut must be accurate.

Feed speed determines the amount of time the workpiece is exposed to the laser beam and hence the amount of energy that can be absorbed. Thus, with other beam factors held constant, cutting depth can be increased as feed speed is reduced.

The productivity of laser cutting systems is related to feed speed, and high speeds are required in some cases. For example, Huber, McMillin, and Rasher suggest that an automated lumber processing system using a laser to cut parts for furniture would be economical at feed speeds of about 50 feet per minute (6). Such speeds would probably require a laser power between 2 to 5 kW operating in the fundamental mode (TEM_{00}).

In other applications, such as cutting intricate shapes in particle- and fiberboard, slower feed speeds may be acceptable. Existing industrial laser profilers in the range of 200 to 800 W can cut as fast as conventional machines used for this type of operation (8). For maximum efficiency, the proper combination of feed speed and power will depend on workpiece thickness, desired kerf width, and wood density.

There is no information in the literature describing the interaction of such factors as focal length, position of the focal point, polarization, and power with feed speed. When this information is fully developed, it should be possible to specify feed speed not only in terms of maximum speed but also in terms of a speed that optimizes such factors as parallelism, degree of char, and smoothness of the cut surfaces.

When cutting wood, a jet of gas is needed to exhaust smoke, to regulate and control excessive burning, and to protect the focusing optics. The type of gas and its pressure significantly affect depth of penetration, feed speed, and quality of the cut. Solid wood is usually cut using a jet of air coaxial with the beam at input pressures up to 60 psi. The use of nonreactive gases yields little improvement (10).

When cutting particle- and fiberboards or other wood composites containing adhesives, the selection of gas and pressure is particularly critical. For these materials, nitrogen or helium is recommended. The proper pressure depends on workpiece thickness and the percentage and type of adhesive present.

For wood cutting, there is no literature available on the effectiveness of gas-jet systems other than coaxial. The authors feel that different jet configurations may significantly improve the cutting process. For example, a second jet placed parallel to the kerf and off the beam axis on the leading edge of the cut is effective for exhausting gases and debris to the rear of the beam (Fig. 6). This reduces the diffraction of the beam and the desired energy level can be maintained with less surface charring. Jet systems of special design may be needed for different classes of materials or even different wood species. A more efficient method of removing vapors and debris from the underside of the board may also be necessary. The amount of vaporized material is far less than the amount of sawdust generated by saws and a small vacuum system may prove sufficient.

Effect of material properties

The interaction of material properties and laser light is complex and is only briefly summarized here. In general, the ability of laser light to cut wood involves the absorption of light, the transformation of light energy into heat, the distribution and rate of heat transfer within the work, and the rate of vaporization in the zone of radiation. Two fundamental optical properties of wood are of significance — absorption and transmissivity.

The amount of laser light absorbed by wood can be expressed by the law of Buger-Lambert and is a positive function of the power density, the coefficient of absorption, the conductivity of light, and the depth of light penetration into the material being cut. The values for conductivity and depth of penetration are not exactly known for laser light of wavelength 10.6 μm, but depend on the moisture content, chemical composition, and density of wood.

For example, consider two wood samples of the same species, density, and thickness, the first wet and the second dry. For light of 10.6 μm, the absorption coefficient of water is less than that of wood. Thus, the overall absorption coefficient for the green wood sample is less than for the dry wood sample because more water is present. Therefore, more power is required to cut wet wood than is required for dry wood if feed speed is held constant.

The amount of light absorbed during a given period of time determines the total energy absorbed. This energy is transformed into heat at the zone of radiation and very high temperatures are generated. The distribution of energy in the workpiece can be expressed as the sum of the energies required to heat the material in and adjacent to the zone of vaporization, to vaporize material, and to move the zone of vaporization in a direction parallel to the beam. The energy required to heat wood is a positive function of conductivity and the temperature required to achieve vaporization. The energy required to vaporize material is dependent on specific energy of vaporization which is mainly related to density, moisture content, and species. The energy required to move the zone of vaporization is a function of the temperature gradient which depends on grain direction and other species-related factors and thickness of the workpiece.

This type of model can explain the influence of such properties as density and grain direction on the ability of lasers to cut wood. Readers desiring greater detail of the thermodynamic processes in laser cutting wood are referred to Arai et al. (2) and Barnekov (4).

Process control

The Southern Forest Experiment Station, in cooperation with others, is developing an automated lumber processing system termed ALPS (9). The process combines elements of computer vision, yield optimization, and laser cutting to replace the rip and crosscut operations in a conventional furniture rough mill.

In ALPS, the surfaces of dressed, dry lumber are optically scanned using computer vision methods to locate and identify surface defects by type. Another computer program then determines the optimum cutting pattern for each board so as to yield the maximum number of parts specified in the cutting bill. Lastly, parts are cut from the lumber using a laser directed by the yield optimization program.

Variability in both the stability of the laser and in wood properties can be expected to affect the cutting process. For example, specific gravity of a given species will differ between and within individual boards as will moisture content. As another example, the quality of cut can differ between cutting along and across the grain.

To compensate for this variability, it will be necessary to control and regulate the laser cutting process using a variety of devices in a real time feedback loop. Consider, for example, a system in which constant cutting speed is desired. Since specific gravity affects feed speed, a radiation source and detector could be placed near the leading edge of the cutting beam. If the density of wood changes, the detector would instruct a supervisory control program to appropriately change the laser output power.

Flexible manufacturing systems such as ALPS are a key part of the factory of the future. Researchers and laser manufacturers generally agree that adaptive online process control is the major component needed for the laser to become a more useful materials processing tool.

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