Gas flow parameters in laser cutting of wood — nozzle design

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Abstract

The Automated Lumber Processing System (ALPS) is an ongoing team research effort to optimize the yield of parts in a furniture rough mill. The process is designed to couple aspects of computer vision, computer optimization of yield, and laser cutting. This research is focused on optimizing laser wood cutting. Laser machining of lumber has the advantage over conventional processing in that it reduces wasted material (i.e., kerf), it can be numerically controlled by computer, and it can make blind cuts around defective areas. Wood cutting is executed using a laser in conjunction with an air-jet nozzle. A supersonic nozzle of new design is used in this study to investigate the effect of high-velocity air on the cutting parameters by 1) maximizing the cutting speed (at a given thickness); and 2) improving the quality of the cut surfaces. A supersonic nozzle was designed and constructed to accelerate pressurized air to Mach = 1.8 at the nozzle orifice. The exit velocity was verified visually by a shadowgraph technique.

Processing lumber by laser cutting has two advantages over conventional saws. First, laser cutting uses a very narrow beam so that the material consumed by it is much less than what is removed by conventional saws (1,2,5,7). It does not generate sawdust, and because laser cutting is flexible, it has more potential applications in the lumber industry than circular saws or bandsaws. Intricate shapes can be made by laser machining, holes can be pierced, and very thin sections of wood can be easily cut (3). Additionally, waste can be minimized by using numerical control to cut nested patterns of parts out of the stock.

Lasers are used to cut wood in conjunction with a stream of air directed at the wood surface (Fig. 1) with the laser beam coaxial to the air stream. The air stream serves three purposes. Mainly, it carries the smoke and debris of combustion out of the kerf (the width of cut) and protects the laser system optics from becoming clouded and obscured. In flushing debris and combustion gases from the kerf, the air stream enhances the laser cutting action by allowing a more direct coupling of the laser energy to the workpiece (4). A reactive gas, such as oxygen, instead of air can serve the above functions as well as actually aid the combustion of the workpiece through chemical reaction. Such gas-jet laser cutting is primarily used in cutting metals, but its significance in wood cutting is still subject to investigation.

This study was conducted to investigate the effect of air stream velocity on cutting speed and cut surface quality. A high-velocity jet of air was obtained through a special nozzle designed to accelerate air flow past sonic velocities to Mach numbers at the nozzle exit. This paper describes the design, manufacture, and testing of such a supersonic nozzle. It presents preliminary results of experiments to determine cutting performance with a supersonic nozzle and discusses implications for further research.

Method and approach

The design of the improved, high-velocity jet nozzle was formulated based on standard engineering principles of one dimension flow, perfect gas, and no heat transfer but extended to include three-dimensional axially symmetric geometry. The general governing equations for flow are described in references (6,8,9) and are not detailed here.

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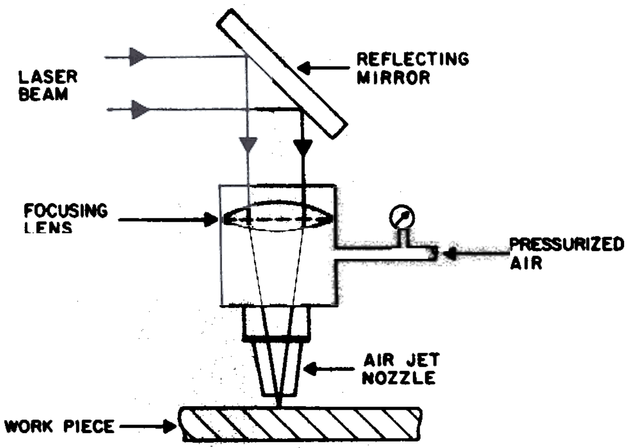

Figure 1. — Schematic air-jet nozzle apparatus.

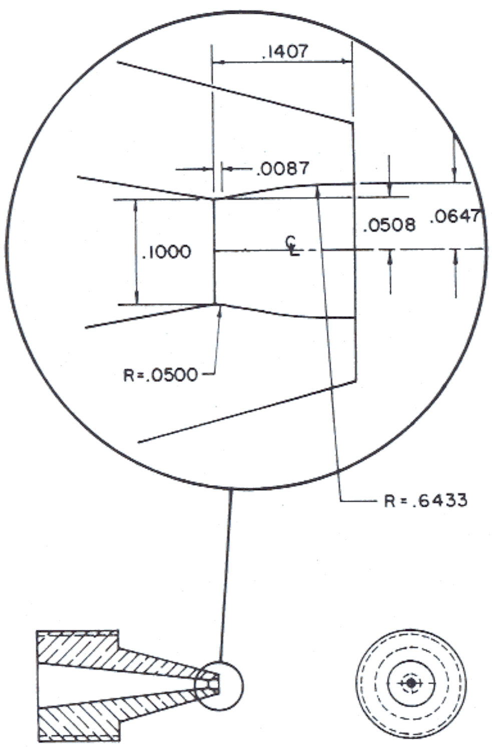

Figure 2. — Working drawing of the nozzle orifice design.

Analysis indicated that uniformity of flow at the nozzle exit is achieved through proper angular design of the diverging profile. In general, it was concluded that the nozzle wall must correspond to a streamlining of flow produced by the impinging wave. In this manner, the flow field was constructed with the direction of the Mach waves from nodes 10, 19, 27,...55 determining the nozzle profile. The flow field was then drawn by computer-aided design to construct the angles yielding a best fit radius to approximate the short line segments that make up the nozzle profile and also to calculate the dimension of the nozzle exit area.

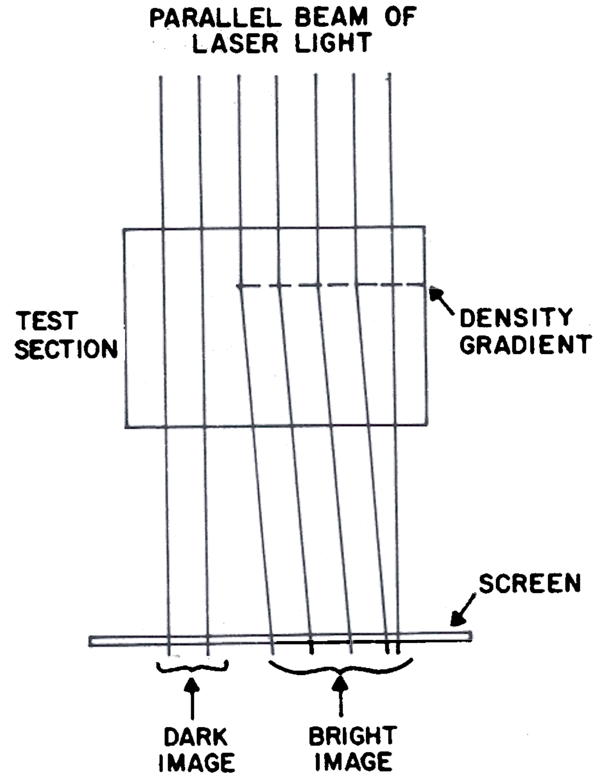

Figure 3. — Illustration of the shadowgraph technique.

A working drawing with these dimensions is shown in Figure 2. The experimental nozzle was manufactured by electrical discharge machining (EDM) and attached to a beam delivery assembly system of a 2000 kW carbon dioxide laser.

Flow verification

To assess the nature of the flow velocity at the laser nozzle exit, a visualization technique was employed. Shock fronts at the nozzle orifice will qualitatively indicate that supersonic velocity has been reached. When the density of a gas changes, as in a shock front, its refractive index also changes. The effect is significant enough to use the shadowgraph method to detect the presence of shock waves in the flow.

In its simplest form, light is aligned as a parallel beam passing through the jet flow and projected on a screen (Fig. 3). If the flow is undisturbed, the screen is uniformly illuminated. But if the light passes along the plane of a shock wave or similar density gradient (Mach wave) the rays on one side of the wave are deflected more than on the other side. The position of the shock wave in the flow is indicated by a darker band and a lighter band close together on the screen.

The apparatus in the visualization procedure consisted of a He-Ne laser fitted with a beam expander. This allowed a beam of parallel light to pass transversely through the nozzle flow. Air at 90 psig was regulated down to charge a plenum to 70 psig. The supersonic nozzle screwed into the plenum, providing an airtight seal to direct the nozzle flow. A screen of white paper was used to project the

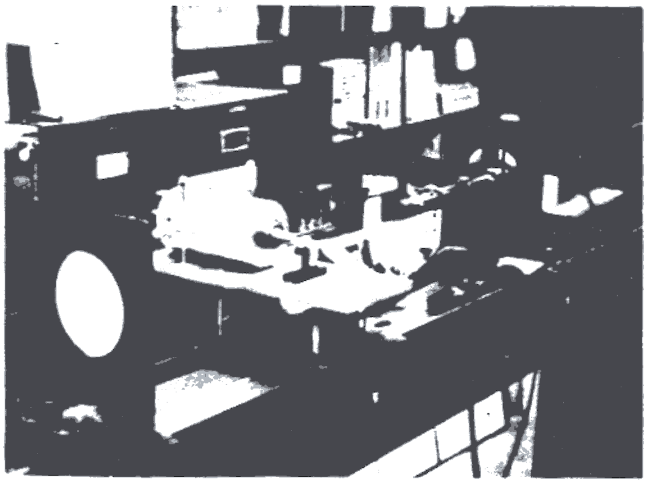

Figure 4. — Flow visualization apparatus.

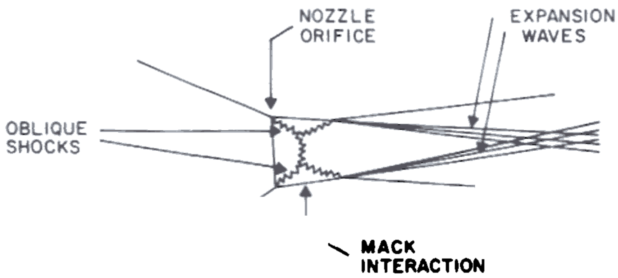

Figure 5. — Oblique shock waves at the nozzle orifice.

shock wave shadow. The screen was translucent and photographs of the shock shadows were made from the side opposite the laser light source. An optical bench was used to mount and align the apparatus (Fig. 4).

The results of the shadowgraphs are quite remarkable. Figure 5 illustrates oblique shocks forming at the nozzle orifice and intersecting at the center of the jet in what is termed a Mach intersection. The jet is forced to contract slightly as it leaves the nozzle. The oblique shocks pass across the jet and reflect back from the opposite side as expansion waves. The expansion waves are clearly visible as dark lines just downstream of the Mach intersection (Fig. 6-top).

In an effort to quantitatively determine flow speed, a wedge was placed in the flow. Oblique shocks should form off the wedge and the angle of the oblique shock may be used to calculate the flow speed. However, the technique did not yield discernible results for either of two wedges placed in the flow (Fig. 6-center and Fig. 6-bottom).

At the nozzle exit, the flow has been overexpanded. That is, pressure at the exit is less than ambient pressure, hence the oblique shocks recompress the flow, adjusting the stream pressure to ambient. The nozzle was designed for a smooth decrease in pressure along the length of the nozzle to match the exit pressure to the ambient. This obviously is not the case. The Mach number at the exit is greater than the design Mach number of 1.8. The

Figure 6. — Photograph of shock wave at the nozzle orifice.

flow speed decreases nonisentropically across the oblique shocks to some Mach number, but the attempt to quantitatively determine the Mach number was unsuccessful due to the three-dimensional nature of the jet.

Implementation and preliminary evaluation

The effect of the high-velocity air stream on laser performance was determined relative to the performance of a standard nozzle of equal orifice diameter. For the same operating conditions of laser power, air pressure, workpiece thickness, and moisture content, a comparison of maximum cutting speed was made using the supersonic nozzle and the standard nozzle. Also of interest was the quality of cut made by the two nozzle designs.

The laser apparatus was also modified to improve beam transmission. Previously, the beam was turned 90 degrees in the horizontal plane by one mirror, then directed vertically down by a second. In the new design, the horizontal beam was turned vertically by only one mirror. The single reflecting mirror was new, thus reducing losses in transmission.

Samples of 1-inch-thick kiln-dried basswood were cut at 1560 W laser power. The nozzle air pressure was adjusted to 70 psig. Cuts were made at successively higher cutting rates until the laser failed to cut through the sample. Maximum cutting speed using the supersonic nozzle was ≥ 180 inches per minute. Maximum cutting speed using the standard nozzle of equal orifice diameter was 120 inches per minute. Thus, an improvement in nozzle design yielded a 50 percent increase in cutting speed. This is significant in that increasing laser power alone does not yield the desired result.

To all appearances, the quality of the cut surfaces did not differ. Extent of charring was about the same, as was the width of the kerf. Clipping (charring of the wood surface on either side of the kerf) caused by diffraction of the laser beam as it passes near the nozzle orifice was not significantly different in the test runs using the supersonic nozzle.

Discussion and conclusions

Preliminary results of this study indicate that high-velocity air significantly improves the cutting rate but not the surface quality in laser cutting of wood. Further work, using optical and electron microscopy, could be conducted to investigate the effect on surface quality using high-velocity air jets. The cutting rate may also depend on other variables of the overall process. As noted before, the mass flux is constant for a given nozzle geometry (i.e., throat area), upstream pressure, and temperature. The effect of mass flux, not velocity, should be investigated. Injection of an active gas into the jet might also enhance the cutting rate as in laser-jet cutting of metals. Finally, other geometries of air (or gas) injection should be considered, such as directing the jet at an angle into the kerf instead of coaxial to the laser beam.

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