

## Cutting performance of a chemical oxygen-iodine laser on aerospace and industrial materials

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### ABSTRACT

A chemical oxygen-iodine laser (COIL) was used for cutting aluminum, titanium, inconel and copper plates. The laser was operated with a stable resonator having an intracavity aperture to produce a circular COIL beam with very few transverse modes. The multimode focal spot diameter was calculated to be 0.24 mm. The new aluminum cut was of particularly high kerf edge quality. These COIL cutting data are compared with an existing theoretical laser cutting model. Using thermophysical data for aluminum, titanium, inconel and copper, this theory agrees very well with the data. To test the versatility of the model, the effects of different assumptions are examined; different assumptions produced very little effect on model predictions at high cutting speeds and a small difference at very slow cutting speeds. Overall, the theoretical model provides good agreement with experiments for a wide variety of metals.

### 1. INTRODUCTION

Lasers have been used successfully for many years in industry for commercial cutting, welding and ablation applications [1]. Traditionally, CO<sub>2</sub> and Nd:YAG lasers are used for such applications. More recently, the chemical oxygen-iodine laser (COIL) has received considerable attention as an industrial device [2-6] because of its short wavelength (1.315 μm), continuous wave (cw) operation, high power and scalability to very high power. The short wavelength has three primary advantages over CO<sub>2</sub>. First, the shorter wavelength of COIL can be focused to a smaller spot size. Second, the COIL wavelength couples better (higher absorption) with most metals [1]. Third, the COIL wavelength can transmit through SiO<sub>2</sub> fiber optics with a loss of only around 0.5 dB/km [1]. While the capital and operating costs of today's COIL devices are higher than today's CO<sub>2</sub> devices, the fact that COIL cuts metals considerably faster than CO<sub>2</sub> lasers [6] may make COIL economically competitive in the high power laser market. Nd:YAG effectively has the same wavelength advantages as COIL, but there are presently no YAG devices with average power levels in excess of 5 kW; this makes Nd:YAG non-competitive in the very high power market.

The chemical oxygen-iodine laser was first demonstrated in 1977 [7]. Brief descriptions of COIL systems can be found in Refs 5 and 6; a detailed overview is presented in Ref. 8. Since its first demonstration, COIL technology has evolved and matured to a sophisticated state for military applications. An excellent summary of basic COIL operation and military COIL technological development is provided by Truesdell *et al.* [8]. Meanwhile, research towards making COIL an industrial device began in the latter half of the 1980's [9]. Long duration, high power industrial COIL operation was addressed in several papers [10-15].

Recently, COIL cutting data has appeared in the literature. Yasuda *et al.* [4] obtained the first results for cutting stainless steel which were quite promising. They also presented a simple two-parameter model and empirically determined these two parameters by fitting the model to their experimental data in order to predict the scaled cutting capability of COIL. Kar *et al.* [5] produced a more complete data base for stainless steel cutting with an inert gas assist. Kar *et al.* also demonstrated the thick-section cutting capability of COIL and developed a simple theoretical cutting model. Carroll and Rothenflue [6] extended the COIL cutting data base to include data for cutting aluminum and carbon steel with an N<sub>2</sub> gas assist, and for carbon steel with an O<sub>2</sub> gas assist. These data were compared with existing COIL, CO<sub>2</sub> and Nd:YAG laser cutting data; it was found that COIL cuts steel approximately three times faster than CO<sub>2</sub> and at approximately the same rate as Nd:YAG. Carroll and Rothenflue also modified the theory of Kar *et al.* to include an empirical correction factor which improved the model's agreement with data. The purpose of this work is to use an improved optical quality beam and investigate the cutting capability of COIL for various aerospace materials, namely aluminum, copper, inconel and titanium. These new experimental data are also compared with the theoretical model developed by Kar *et al.* and modified by Carroll and Rothenflue.

### 2. EXPERIMENTAL SETUP

The Research Assessment, Device Improvement Chemical Laser (RADICL), located at the Air Force Research Laboratory at Kirtland Air Force Base, NM, was used for all of these cutting tests. The laser was operated with a stable resonator which consisted of a highly reflective 25 m radius of curvature mirror as one end mirror of the resonator, two highly reflective flat mirrors to fold the beam within the resonator, and a partially reflective flat outcoupler as the other end mirror of the resonator oriented in a Z-pass (or 3-pass) configuration. The resonator length, which is the distance between the two end mirrors was 710 cm. To reduce the large number of transverse modes typical of a stable resonator with a large aperture, a 2.54 cm diameter intracavity aperture was placed near the outcoupler. Using Equations (17-51) and (19-10) from Siegman [16] an estimate of the maximum number of modes which could be lasing is calculated to be 34; this is significantly fewer than the estimated 200 modes with the rectangular beam used by Kar *et al.* [5] and Carroll and Rothenflue [6]. The advantage of using

the apertured Z-pass resonator configuration is that it permits a much better optical quality beam while maintaining typical RADICL power levels by increasing the total gain length via the three passes through the COIL gain medium, i.e. there would have been a significant power loss if a single-pass apertured resonator had been utilized. The focusing lens ( $f_1=10.8$  cm) was located 780 cm from the laser outcoupler which produced a circular focal spot calculated to be 0.24 mm in diameter, Fig. 1. The target was situated so that the focal point was located approximately 1 mm into the workpiece. The power on target ranged from 2 to 5.7 kW.

The gas assist nozzle for all tests was the same type of nozzle as the one used by Kar *et al.* [5] and Carroll and Rothenflue [6]. The nozzle was made from 16 mm (0.625 inch) diameter stainless steel tubing that was flattened and shaped to form a rectangular nozzle. The nozzle exit dimension was approximately 1.5 mm by 27 mm. The gas assist nozzle was oriented horizontally so the long dimension was lined up with the cut direction (or kerf) and was fixed at a 45 degree angle from

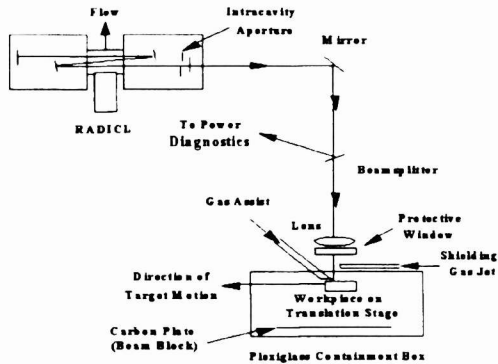


Fig. 1 Experimental layout for COIL cutting experiments.

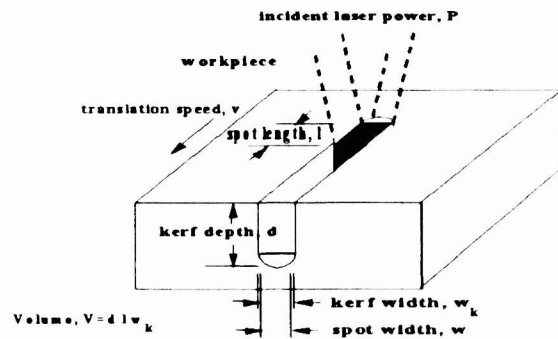


Fig. 2 Laser processing parameters

normal to the target.

The targets for the tests consisted of metal plates which were mounted on a stepper motor-controlled, horizontal translation stage (capable of speeds up to 3.0 m/min) and were scanned through the focal region at constant speed. Scans were conducted at various speeds and the cut depth was measured later.

The kerf width  $w_k$  was measured after the tests using a caliper. As observed by Kar [5] and Carroll [6], for a given cut, the kerf width generally increased with increasing cut depth. In these cases, an average kerf width was obtained by summing the width at several locations along the edge of the target and dividing this result by the number of measurements.

### 3. CUTTING RESULTS

One new cut was made through aluminum with a nitrogen gas assist. Extremely good kerf edge quality (very little dross) was obtained when this aluminum workpiece of thickness 9.83 mm was cut at a speed of  $v = 16$  mm/s (0.96 m/min), beam with focal spot diameter 0.24 mm (average kerf width of 0.635 mm), power of 4.7 kW, and with the nitrogen cutting assist gas having a gauge pressure of roughly 90 psia. A photograph of this excellent aluminum cut is shown in Fig. 3.

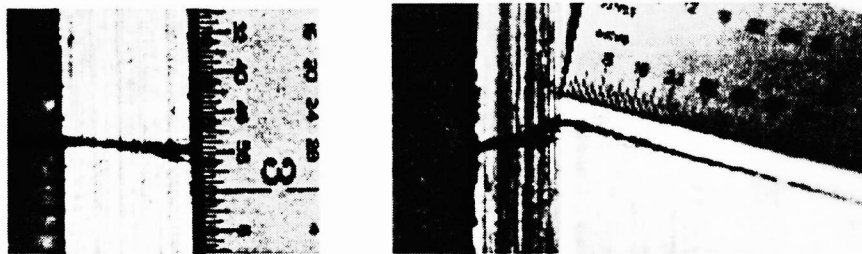


Fig. 3 photographs of the high quality aluminum cut.

The cutting data are presented in Figs. 4-7 along with the theoretical predictions (discussed in Section 4). The aluminum cutting data from Carroll and Rothenflue [6] have been added to Fig. 4 for comparison and completeness. The fact that the new aluminum data point obtained with a much better beam quality is consistent with the previous aluminum data illustrates the utility of presenting laser cutting data in the form of  $d/P$  as a function of  $w_k v$ , Fig. 4. The data taken for inconel 600, titanium and copper are shown in Figs. 5-7, respectively. Only one successful copper cut was performed. As in the case of the new aluminum cut, extremely good kerf edge quality (very little dross) was also obtained for copper.

The data are presented in these figures as the ratio of the cut depth  $d$  to incident laser power  $P$ , as a function of the product of the kerf width  $w_k$  and the cutting velocity  $v$ , i.e.  $d/P$  versus  $w_k v$ . The reason for presenting the data in this fashion is twofold. First, these four variables are the principle materials processing parameters, Fig. 2. The combination of these

parameters into a single two-dimensional plot allows the comparison of cutting data from different types of lasers with different wavelengths. The presentation of laser cutting data in this fashion permits appropriate comparisons between different lasers having different powers and focused beam sizes. Second, the theory, to which the data are compared in Section IV, has the ratio  $d/P$  on the left hand side of the equation as a function of  $w_k v$  on the right hand side of the equation, Eq. (1); this theory is general to any type of laser.

#### 4. COMPARISON TO THEORETICAL MODEL

A simple mathematical model of laser cutting was developed by Kar *et al.* [5]. A modified form of this theory was presented by Carroll and Rothenflue [6]. The simplified form of the theory is given by

$$\frac{d}{P} = \frac{A_0}{w_k v + A_3 \sqrt{w_k v} + A_4} \quad (1)$$

where  $d$  and  $w_k$  are in units of mm,  $v$  is in m/min, and  $P$  is in kW, and the detailed definition of the  $A_0$  and  $A_3$  terms can be found in Ref. 5. The principle materials processing parameters are illustrated in Fig. 2. The  $A_0$  term is related to the absorptivity of the substrate at the laser-material interaction zone, the term containing  $A_3$  describes the energy lost to heat conduction into the solid substrate. The only difference between the original theory of Kar *et al.* and Carroll and Rothenflue is the inclusion of the  $A_4$  term in the denominator of Eq. (1). Carroll and Rothenflue [6] showed that Eq. (1) modeled the data reasonably well when  $A_4 = 0$  (equivalent to the original theory of Kar *et al.*), but tended to curve upwards too steeply for lower values of  $w_k v$  [this effect is a consequence of the fact that Eq. (1) goes to infinity as  $w_k v$  goes to zero when  $A_4 = 0$ ]. Thus, it was clear that there was an effect unaccounted for in Kar *et al.*'s theory which became more significant at smaller values of  $w_k v$ . As such, to better match the data, Carroll and Rothenflue added an empirical modification to the theory by simply adding a constant  $A_4$  to the denominator of the right hand side of Eq. (1). Carroll and Rothenflue found that setting  $A_4 = 0.22$  provided an excellent fit to the stainless steel data as well as very good agreement with aluminum cutting data [6]. The physical significance of such a term is probably the inclusion of convection, radiation and/or plasma absorption, which were all assumed negligible in the derivation of Eq. (1). Plasma absorption was addressed by Kar *et al.* in Ref. [17], however, the resulting model was far more complex and not in any better agreement than the simple model of Eq. (1). While the  $A_4$  term is a correction factor for the theory, it is important to point out that Eq. (1) retains the basic physical underpinnings of the original cutting theory.

The values of thermophysical properties, that are reported in Table 1 from Refs. [18-20], are used in this study for numerical calculations by using Eq. (1). These theoretical results are compared with experimental data in Figs. 4-7. The absorptivity of the workpiece was chosen to be the calculated values based on the Hagen-Rubens relation for the liquid phase at the melting temperature [21]. The absorptivities for Al, Cu, Ni and Ti are taken to be 0.18, 0.14, 0.29 and 0.39 respectively [21].

Table 1. Typical values for the thermophysical properties of aluminum, inconel, titanium, and copper (Refs.18-20). Inconel values with a  $\approx$  in front are estimates taken from nickel.

Thermophysical Property	Aluminum	Inconel	Titanium	Copper
Density, $\rho$ [kg/m <sup>3</sup> ]	2702	8250	4500	8960
Melting point, $T_m$ [K]	933	1643	1941	1357
Boiling point, $T_b$ [K]	2792	$\approx$ 3180	3560	2835
Specific heat, $c_p$ [J/kg-K]	897	$\approx$ 444	523	385
Thermal conductivity, $k$ [W/m-K]	237	15	21.9	401
Thermal diffusivity, $\alpha = k/(\rho c_p)$ [m <sup>2</sup> /s]	$9.78 \times 10^{-5}$	$4.10 \times 10^{-6}$	$9.31 \times 10^{-6}$	$1.16 \times 10^{-4}$
Latent heat of melting, $L_m$ [J/kg]	$3.97 \times 10^5$	$\approx 2.92 \times 10^5$	$3.65 \times 10^5$	$2.05 \times 10^5$
Latent heat of boiling, $L_b$ [J/kg]	$10.7 \times 10^6$	$\approx 6.38 \times 10^6$	$8.89 \times 10^6$	$4.80 \times 10^6$
<b>Theoretical Cutting Coefficients</b>				
Absorptivity at 1.315 $\mu$ m	0.18	$\approx$ 0.29	0.39	0.14
A0	4.1079	2.3613	4.2299	1.5222
A3	2.1423	0.4987	0.7853	2.6333

For the purpose of utility, it is simplest and most convenient to assume thermophysical properties at room temperature; thermophysical properties of many materials at temperatures as high as the melting temperature are often hard, if not impossible, to track down in the literature. Most of the molten material is usually removed from the kerf by the assist gas during metal cutting. Only a fraction of the melt is vaporized. For simplicity, the boiling coefficient discussed in Ref. 5 will be assumed to be zero.

Using the thermophysical properties and absorption coefficients listed in Table 1 [18-20],  $l = w_k = 0.24$  mm and  $T_0 = 293$  K, the theoretical cutting coefficients  $A_0$  and  $A_3$  were computed, Table 1. Eq. (1) is plotted in Figs. 4-7 for aluminum, inconel, titanium and copper, respectively. These figures compare the theoretical predictions when the  $A_4$  term is 0.0 and 0.22; the value of  $A_4 = 0.22$  is chosen because it produced good agreement with both stainless steel and aluminum cutting data in Ref. [6]. It is clear from Figs. 4-7 that Eq. (1) models the data reasonably well, but when  $A_4 = 0.0$  the curve rises upwards too

steeply for lower values of  $w_k v$ . When  $A_4 = 0.22$ , the model is in better agreement with the data. Until data are acquired having values of  $w_k v$  less than 0.1, it is impossible to determine what value of  $A_4$  would provide the best fit to the data.

Overall, including the data from Refs. [5] and [6], the simple model of Eq. (1) is in good agreement with cutting data for all six metals studied (stainless steel, carbon steel, aluminum, inconel, titanium and copper). The model is generally in better agreement with data when using  $A_4 = 0.22$  than when using  $A_4 = 0.0$  [equivalent of Eq. (1)]; this is particularly true at low values of  $w_k v$ . It is interesting that a value of 0.22 for the  $A_4$  term works well for all of the metals investigated; this may suggest that the  $A_4$  term is not (or only weakly) material dependent, i.e., not (or only weakly) dependent upon thermophysical properties. There are some disagreements between the model and data, but this can be expected because of the simplicity of the model. While the model is by no means perfect, it is felt that reasonable estimates of true laser cutting speeds can be determined using Eq. (1), known thermophysical properties to determine the  $A_0$  and  $A_3$  coefficients, and a value of  $A_4$  of approximately 0.22. This makes the theoretical model an extremely useful tool for industrial applications, especially when the simplicity of the model is considered.

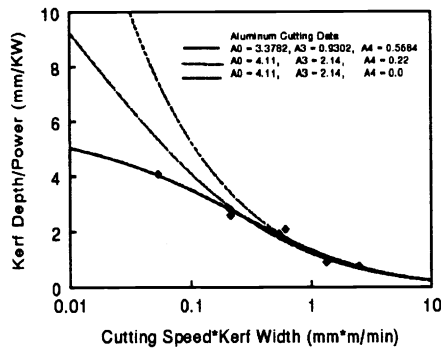


Fig 4. COIL Aluminum Cutting Experimental Data with Empirical Model

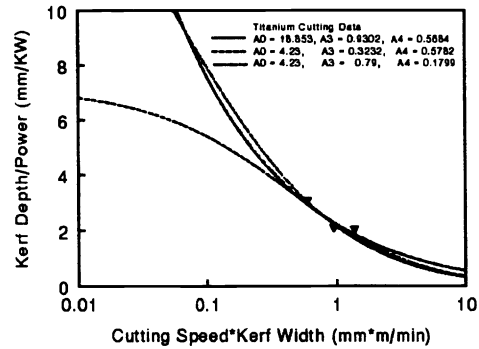


Fig 6. COIL Titanium Cutting Experimental Data with Empirical Model

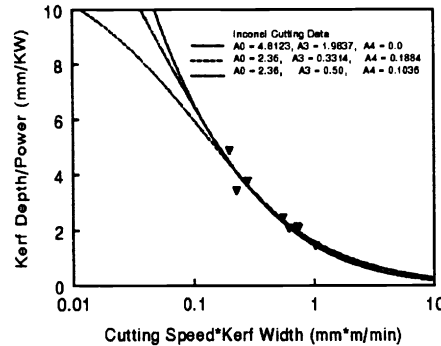


Fig 5. COIL Inconel Cutting Experimental Data with Empirical Model

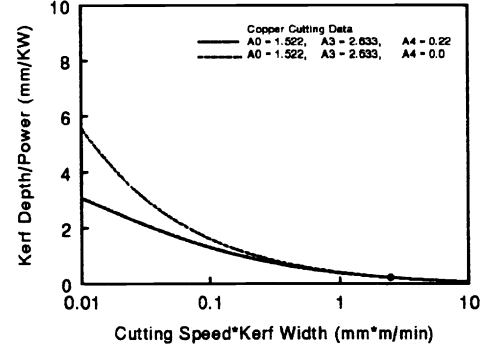


Fig 7. COIL Copper Cutting Experimental Data with Empirical Model

## 5. SUMMARY AND CONCLUDING REMARKS

A chemical oxygen-iodine laser (COIL) was used for cutting four common aerospace materials, namely aluminum, titanium, inconel and copper plates. The laser was operated with a stable resonator having an intracavity aperture to produce a circular COIL beam with very few transverse modes. The multimode focal spot diameter was calculated to be 0.24 mm. The new aluminum cut was of particularly high kerf edge quality.

The speed at which COIL cuts metals makes this laser an intriguing industrial device. While COIL and Nd:YAG cut metals at approximately the same rate (the wavelengths are nearly the same), the Nd:YAG has power levels which are limited to roughly 5 kW or less (at the present time) and as such it is difficult (if not impossible) for Nd:YAG to cut very thick metals. Since COIL cuts metals significantly faster than CO<sub>2</sub> lasers, and Nd:YAG lasers are presently limited in power level, COIL has considerable potential as a high power (>5 kW) industrial laser. The fact that the COIL wavelength is also fiber deliverable makes this laser extremely attractive for many applications.

Overall, the simple theoretical model is in good agreement with cutting data for a wide variety of metals (aluminum, inconel, titanium, copper, stainless steel, and carbon steel). The model is generally in better agreement with data when using  $A_4 = 0.22$  than when using  $A_4 = 0.0$ ; this is particularly true at slow cutting speeds (low values of  $w_k v$ ). It is interesting that a value of 0.22 for the  $A_4$  term works well for all of the metals investigated; this may suggest that the  $A_4$  term is not (or only

weakly) material dependent. There are some disagreements between the model and data, but this is to be expected because of the simplicity of the model. While the model is by no means perfect, it provides reasonable estimates of true laser cutting speeds. This makes the theoretical model an extremely useful tool for industrial applications, especially when the simplicity of the model is considered.

To test the versatility of the model, the effects of different assumptions were examined (not shown for brevity). Qualitatively, the different assumptions investigated produced very little effect on model predictions at high cutting speeds and small differences at very slow cutting speeds. For the purpose of utility, it is easiest to assume thermophysical properties in the solid state at room temperature because these properties are readily available for all common metals. Also, since the boiling coefficient is generally unknown, it is simplest to assume the boiling coefficient is zero. These assumptions should result in the reasonable prediction of cutting speeds for different metals.

To obtain a better empirical value for  $A_4$  as a function of the material being cut, more data should be taken at slower cutting speeds. The physical significance of the  $A_4$  term still needs to be established; it is likely to be the inclusion of convection, radiation and/or plasma absorption, which were all assumed negligible in the derivation of the original model. The theory still needs to have a reactive term added to model  $O_2$  gas assist data.

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