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Experimental Analysis of the Materials Processing Performance of a Chemical Oxygen-Iodine Laser (COIL)

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Abstract

A chemical oxygen-iodine laser (COIL) was used for cutting aluminum and carbon steel, and for depositing a ceramic coating on a substrate. Cut depths of 20 mm were obtained in aluminum and 41 mm in carbon steel using an N_2 gas assist and 5-6 kW of power on target. The same laser at the same power level produced a cut depth of 65 mm in carbon steel with an O_2 gas assist; a low quality cut to a depth of nearly 100 mm in carbon steel was demonstrated. These data are compared with existing COIL and CO_2 laser cutting data. COIL cuts carbon steel and stainless steel at approximately the same rate. For a given cut depth, power and spot size, COIL cuts steel approximately three times faster than a CO_2 laser using an inert gas assist. COIL cutting speeds in carbon steel are improved by approximately a factor of three when an O_2 assist is used in lieu of an N_2 gas assist. With an N_2 gas assist, COIL cuts aluminum at approximately the same rate as CO_2 cuts steel. The cladding experiments were conducted in a nitrogen gas environment. Optical micrographs of the experiments are presented for the morphology of the clad surface and the cross section of the cladding zone.

1. Introduction

Lasers made their debut for materials processing in 1965. Since that time, materials processing with CO_2 and Nd:YAG lasers has evolved into a mature technology.[1] Other laser technologies which are still evolving for materials processing applications are CO, excimer, HF/DF and the chemical oxygen-iodine laser (COIL).[2-4] Of these other laser technologies, COIL is of particular interest because of its short wavelength (1.315 μm), high scalable continuous wave (cw) power, and excellent beam quality (due to very small density gradients in its laser cavity).

The short wavelength has three primary advantages over CO_2. First, the shorter wavelength of COIL can be focused to a smaller spot size. Second, the COIL wavelength couples better (higher absorption) with materials such as steel and aluminum.[1] Third, the COIL wavelength can transmit through SiO_2 fiber optics with a loss of only around 0.5 dB/km.[1] While the capital and operating costs of today's COIL devices may make them economically uncompetitive with CO_2 devices in the low to mid power level markets, COIL has considerable potential for high power (> 5 kW) applications. Further, while Nd:YAG effectively has the same wavelength advantages as COIL, there are presently no Nd:YAG devices with average power levels in excess of 5 kW; this makes Nd:YAG a non-competitor in the high power market.

The chemical oxygen-iodine laser was first demonstrated in 1977.[5] Briefly stated, a chemical laser is a device which uses a series of chemical reactions to obtain excited atoms (or molecules) for subsequent lasing. The chemical oxygen-iodine laser (COIL) utilizes an energy transfer from the singlet delta electronically excited state of oxygen [O_2 ($^1\Delta$)] to I_2 to dissociate the iodine molecule. This process is followed by an energy transfer from other O_2 ($^1\Delta$) molecules to the liberated iodine atoms, thus providing the energy for the atomic iodine laser transition of interest. A block diagram of a typical COIL system is illustrated in Fig. 1. Since its first demonstration, COIL technology has evolved and matured to a sophisticated state for military applications. Good summaries of military COIL technological development are provided by Truesdell *et al*.[6] and Avizonis and Truesdell.[7] Meanwhile, research towards making COIL an industrial device began in the latter half of the 1980's.[8] Long duration, high power industrial COIL operation has been addressed in several papers.[9-14] General issues associated with the industrialization of COIL were discussed by Scott and Truesdell.[15]

To test the materials processing performance of COIL, cutting and cladding experiments were performed with a 10 kW class COIL device. The cutting experiments, and comparisons with other data and a theoretical model are discussed in Section 2. The cladding experiments and results are discussed in Section 3.

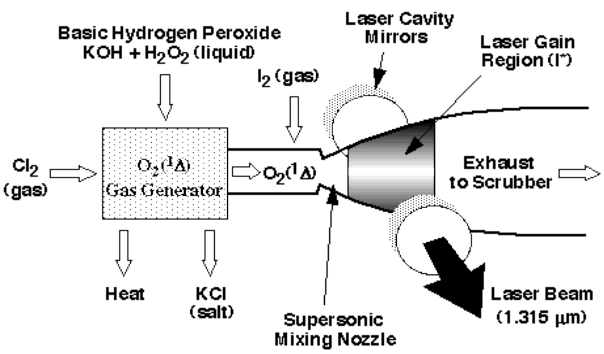

Fig. 1 Block diagram illustrating the major components of a typical COIL system.

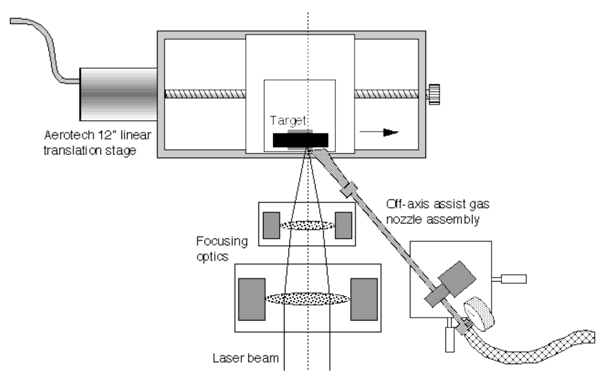

Fig. 2 The experimental set up for the thick section metal cutting experiments with RADICL.

2. Cutting Experiments

Recently, COIL cutting data has appeared in the literature. Yasuda *et al.*[16] obtained the first results for cutting stainless steel which were quite promising. Kar *et al.*[17] produced a more complete data base for stainless steel cutting with an inert gas assist. This work extends the COIL cutting data base to include data for cutting aluminum and carbon steel with an N_2 gas assist, and for carbon steel with an O_2 gas assist. These data are compared with existing COIL and CO_2 laser cutting data.

2.1 Experimental Setup

The Research Assessment, Device Improvement Chemical Laser (RADICL), located at the U.S. Air Force's Phillips Laboratory, was used for all of these cutting tests. To maximize power output, a stable resonator was used on RADICL which consisted of a highly reflective 10 m radius of curvature feedback mirror and a partially reflective flat outcoupler spaced 3 m apart. Because of the use of a stable resonator, a large number of transverse modes were present in the outcoupled beam; this prevented the beam from being focused to a diffraction limited spot. A combination of lenses was used to focus the beam on the target, Fig. 2. The target was situated so that the focal point was located 1 mm into the workpiece. The rectangular multimode focal spot was 1.8 mm wide by 3.0 mm long. The spot was horizontally oriented such that the leading edge of the spot was the smallest dimension. The power on target ranged from 5 to 6.5 kW.

The gas assist nozzle for all tests was the same large nozzle used by Kar *et al.*[17] The nozzle was made from 19.1 mm (0.75 inch) diameter stainless steel tubing that was flattened and shaped to form a rectangular nozzle. The nozzle exit dimension was approximately 1.0 mm by 22.9 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 normal to the target, Fig. 2. The gas assist consisted of either nitrogen at a pressure of 793 kPa (115 psia) or oxygen at a pressure of 310 kPa (45 psia).

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 scanned through the focal region at constant speed. Scans were conducted at various speeds and the cut depth was measured later. The aluminum targets were 38.1 mm (1.5 inches) thick and the carbon steel targets were 76.2 mm (3 inches) thick. For one test, a 101.6 mm (4 inches) carbon steel target was used. None of the data reported in this work actually cut through the entire thickness of the target. Since it is possible that slightly higher cut speeds might be obtained when a complete cut is made and molten material is allowed to blow out the back of the cut, these data may represent a slight underestimate of COIL cutting speeds.

A schematic of the laser processing parameters is shown in Fig. 3. d is the kerf depth given in units of mm, w_k is the kerf width given in units of mm, v is the velocity of the scanning laser beam in m/min, and P is the power of the incident laser beam in kW.

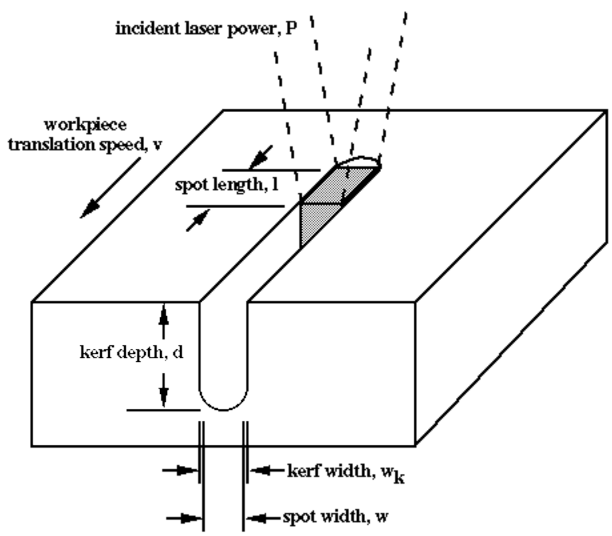

Fig. 3 Laser processing parameters.

2.2 Aluminum and Carbon Steel Experiments and Comparison with Other Cutting Data

Before any aluminum or carbon steel cutting tests were performed, two cuts were made in stainless steel to verify that the experimental setup and conditions were comparable to those of Kar *et al.*[17] The two tests gave results which fall directly on Kar's cutting data, Fig. 4. Six cutting tests were then made into carbon steel (A36) with a nitrogen gas assist at various cutting speeds v, Fig. 4 The cut speeds varied from 0.03 to 1.0 m/min. As expected, for a relatively constant power level (5.7-6.5 kW) and spot size, as the the scanning speed increases, the cut depth decreases. The average kerf widths were 1.65-2.54 mm with the larger kerf widths occurring for the slower cutting velocity cases. It is clear from Fig. 4 that COIL cuts carbon steel and stainless steel at approximately the same rate; this result is most likely a tradeoff between the effects of a higher absorption coefficient (more power absorbed) and a higher thermal conductivity (more energy dissipated) in carbon steel than in stainless steel. Figure 4 presents a comparison of inert gas assist steel cutting with a COIL versus that with a CO_2 laser.[18] Most importantly, this figure shows that COIL cuts steel faster than CO_2 by approximately a factor of 3 for a fixed *d/P* and w_k.

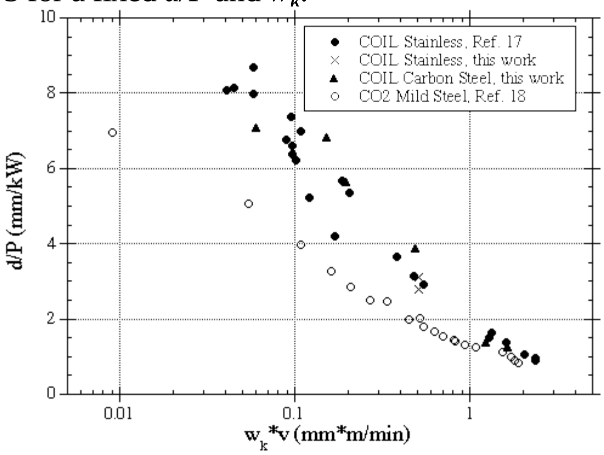

Fig. 4 Comparison of inert gas assist steel cutting data with a COIL device and with a CO_2 laser.

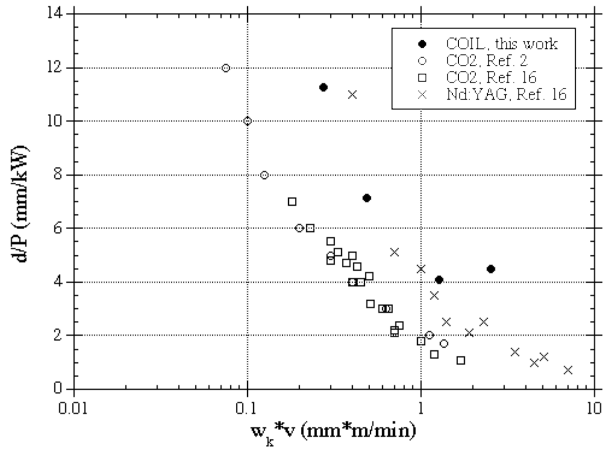

Fig. 5 Comparison of O_2 gas assist carbon steel cutting data with a COIL device and with a CO_2 laser.

A comparison of these data with Nd:YAG cutting data from Ref. 18 indicates that COIL and Nd:YAG cut steel at approximately the same rate (not shown). Since the wavelength of COIL (1.315 μm) and Nd:YAG (1.06 μm) are roughly the same, this is not a surprising result.

Four cutting tests were then made into carbon steel (A36) with an oxygen gas assist at various cutting speeds *v*, Fig. 5. For safety reasons, the assist pressure was reduced to 310 kPa (45 psia) to reduce the amount of reaction with oxygen. The cut speeds varied from 0.12 to 1.0 m/min. Again, as expected, for a relatively constant power level (5.7-7.2 kW) and spot size, as the the scanning speed increases, the cut depth decreases. The kerf widths at the front face of the workpiece were notably larger (2.0-2.5 mm) when the O_2 assist was used. For the O_2 assist tests, the cut quality was significantly reduced from that of the inert gas experiments. The use of more sophisticated oxygen assist technology would probably result in a higher quality cut. A comparison of Figs. 4 and 5 shows that the O_2 gas assist substantially improves the cutting speed for a given power, cut depth, and kerf width; for a fixed *d/P* and w_k, there is approximately a factor of 3 increase in cutting speed with the O_2 gas assist above that when using an inert gas assist. A comparison of O_2 gas assist steel cutting with a COIL versus that with a CO_2 laser[2,16] and an Nd:YAG laser[16] is shown in Fig. 5. With an oxygen gas assist and for a fixed *d/P* and w_k, COIL cuts approximately 2 to 3 times faster than a CO_2 laser. As found for an inert gas assist, COIL and Nd:YAG also cut carbon steel at approximately the same rate when using an oxygen gas assist.

A long duration test was performed to cut a 4”x4”x4” block of carbon steel at a speed of 0.107 m/min. Because of thermal management issues associated with the long run time of the RADICL laser, the power level for this test was only 5.4 kW. The O_2 gas assist pressure was increased to 483 kPa (70 psia) to improve the momentum transfer through the workpiece. While there was a significant amount of melting of the workpiece during this test (making it difficult to adequately judge a kerf width), the beam cut to a depth of 96.5 mm. The amount of melting was most likely enhanced by the increase in the oxygen assist pressure. Despite the low quality of the cut, this test demonstrates the ability of COIL to cut fairly thick steel.

Six cutting tests were made into aluminum with a nitrogen gas assist at various cutting speeds *v*, Fig. 6 The cut speeds varied from 0.03 to 1.50 m/min. As anticipated, for a relatively constant power level (5-6.3 kW) and spot size, as the the scanning speed increases, the cut depth decreases. All of the kerf widths were 1.65-1.78 mm (approximately the beam spot width). Figure 6 shows that COIL cuts aluminum nearly as fast CO_2 cuts steel.[18] This finding may have important implications for COIL as an excellent laser for aluminum cutting/welding/drilling applications.

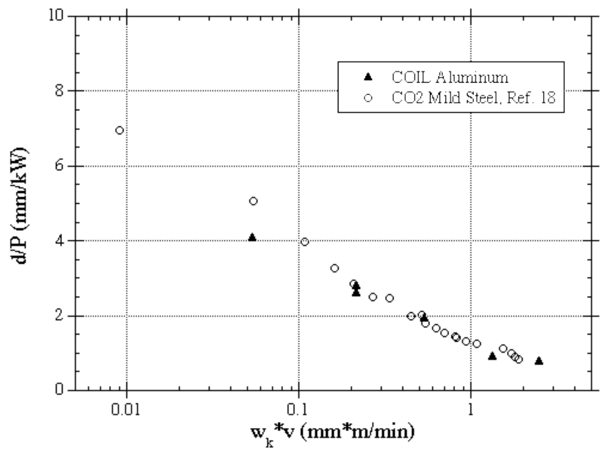

Fig. 6 Comparison of COIL cutting of aluminum with CO_2 cutting of steel. These data were taken with an inert gas assist.

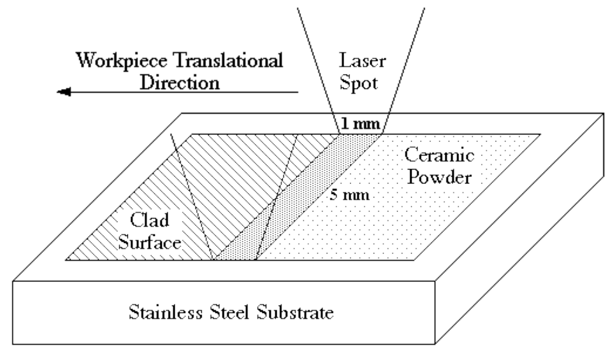

Fig. 7 Schematic of cladding experiement.

3. Cladding Experiments

The ability of a laser beam to induce localized heating is utilized extensively to perform various types of materials processing. However, a large area of the substrate surface can be melted in a single pass of a scanning laser beam of very high power. For instance, a 10 kW laser beam with a rectangular spot of size 10mm x 1mm gives rise to an intensity of 10^5 W/cm^2 that can be used to produce a melt pool of width 10 mm in a single pass of the laser beam. Therefore, high power lasers can be used for large-area processing such as laser hardening, surface alloying, thin film deposition, coating, cladding and materials removal.

Laser cladding is used to improve the oxidation, corrosion and wear resistant properties of an engine part or any other structure. This technology provides a means of utilizing inexpensive materials for high temperature applications such as aircraft engines by depositing materials of improved properties on the workpiece. Due to rapid cooling inherent in laser materials processing, the molten clad material solidifies rapidly leading to the formation of nonequilibrium alloys with meatstable microstructures. These novel microstructures enhance the properties of the clad material. Both metal and ceramic coatings have been applied to improve the surface properties of the workpiece. This section of the paper is concerned with the experimental studies of cladding stainless steel substrates with ceramics using COIL.

3.1 Experimental Procedure

The laser cladding experiments were also performed with the RADICL device, Section 2.1. The output laser beam of this device was focused into a rectangular spot of length and width 5 mm and 1 mm, respectively, on the surface of a preplaced cladding powder mixture, Fig. 7. For all of the experiments, stainless steel substrates of dimension 87mm x 49mm x 6.5mm were used and the mixture of zirconium oxide (ZrO_2) and aluminum (Al) cladding powder was preplaced on the substrate in the form of a rectangular layer of dimension 25mm x 4mm x 2mm. The compositions of ZrO_2 and Al are specified in Figs. 8-11. The substrate with this cladding powder mixture was placed on a translation stage that was moved at a speed of 0.5 cm/s relative to the laser beam for all experiments. The laser beam was kept stationary and it was so aligned that the length of the spot was in the transverse direction. The experiments were conducted in an environment of N_2 gas whose pressure was slightly above 1 atm.

3.2 Cladding Results and Discussion

Ceramic coatings were deposited on stainless steel substrates by carrying out experiment under the conditions discussed in Section 3.1. Optical micrographs for two coatings are presented in Figs. 8-11. Figures 8 and 9 represent results for 4.65 kW of incident laser power and a cladding powder mixture of nominal composition 95.08 wt% ZrO_2 and 4.92 wt% Al. Figures 10 and 11 are results for 4.72 kW of incident laser power and a cladding powder mixture of nominal composition 80.04 wt% ZrO_2 and 19.96 wt% Al. Figure 8 shows fish-scale-like morphology while Figure 10 shows relatively smoother texture although it has a few cracks. The smooth texture in Fig. 10 may be due to excessive Al that melts and redistributes in the clad melt pool and provides a binding mechanism for the ceramic grains. However, the exact reason for the presence of the cracks, which may be due to thermal and metallurgical transformation stresses, is unknown at present. Further studies are needed to better understand the effects of the Al content on the surface morphology and cracks.

Figures 9 and 11 show the cross section of the clad, clad-substrate interface and the substrate melt pool. The sharp clad-substrate interfaces in these two micrographs indicate that the substrates are diluted very little by the ceramic cladding material. This means that the properties of the substrate will be unaffected by the cladding material due to ceramic coating. However, the size of the substrate melt pool is fairly large. This is because the ceramic powder has higher melting temperature than the stainless substrate and therefore, a large amount of heat is lost to the substrate during the melting and solidification of the cladding material. A large melt pool in the substrate can alter the substrate properties near the clad-substrate interface due to rapid heating and cooling of the fusion zone. Further studies are needed to minimize the change in substrate properties near the clad-substrate interface.

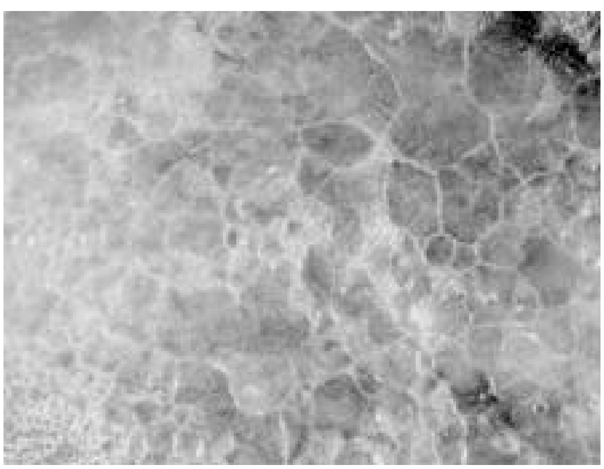

Fig. 8 Surface morphology of a laser ceramic clad. Magnification: 25. Cladding mixture: 95.08% ZrO_2 and 4.92% Al by wt. Substrate: Stainless steel. Laser parameters: Incident power = 4.65 kW, Scanning speed = 0.5 cm/s, 4mm x 1mm rectangular spot.

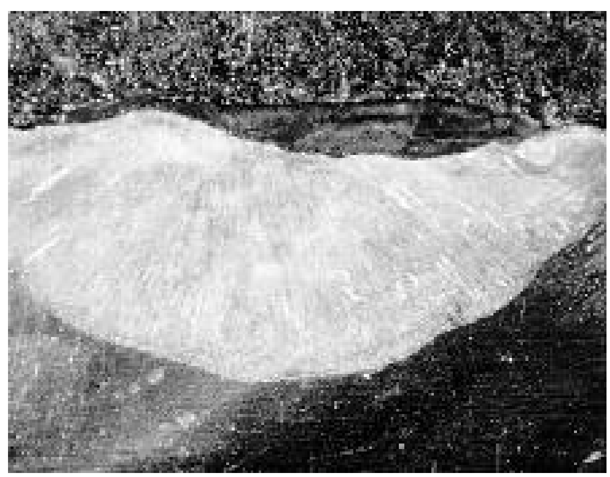

Fig. 9 Cross sectional view of the ceramic clad, clad-substrate interface and substrate melt pool. Magnification: 18. Cladding mixture: 95.08% ZrO_2 and 4.92% Al by wt. Substrate: Stainless steel. Laser parameters: Incident power = 4.65 kW, Scanning speed = 0.5 cm/s, 4mm x 1mm rectangular spot.

Fig. 10 Surface morphology of a laser ceramic clad. Magnification: 35. Cladding mixture: 80.04% ZrO_2 and 19.96% Al by wt. Substrate: Stainless steel. Laser parameters: Incident power = 4.72 kW, Scanning speed = 0.5 cm/s, 4mm x 1mm rectangular spot.

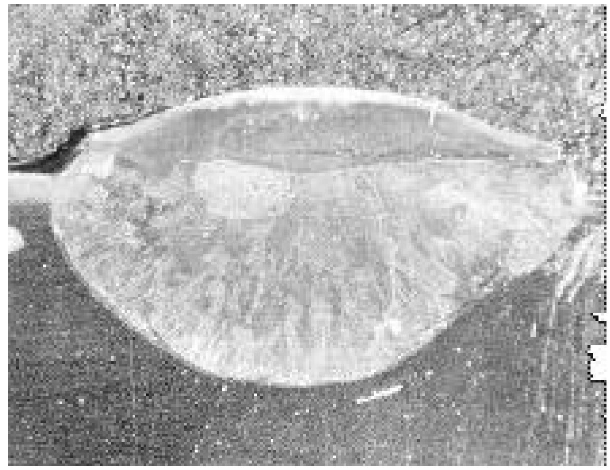

Fig. 11 Cross sectional view of the ceramic clad, clad-substrate interface and substrate melt pool. Magnification: 18. Cladding mixture: 80.04% ZrO_2 and 19.96% Al by wt. Substrate: Stainless steel. Laser parameters: Incident power = 4.72 kW, Scanning speed = 0.5 cm/s, 4mm x 1mm rectangular spot.

4. Summary and Concluding Remarks

A chemical oxygen-iodine laser (COIL) was used for cutting aluminum and carbon steel; these data represent an addition to the minimal COIL cutting database which exists for stainless steel. Cut depths of 20 mm were obtained in aluminum and 41 mm in carbon steel using an N_2 gas assist and 5-6 kW of power on target. The same laser at the same power level produced a cut depth of 65 mm in carbon steel with an O_2 gas assist; a low quality cut to a depth of nearly 100 mm in carbon steel was demonstrated.

COIL cuts carbon steel and stainless steel at approximately the same rate. When these data are compared with existing CO_2 laser cutting data, it is found that for a given cut depth, power and spot size, COIL cuts steel approximately three times faster than a CO_2 laser using an inert gas assist. COIL cutting speeds in carbon steel are improved by approximately a factor of three when an O_2 assist is used in lieu of an N_2 gas assist. With an N_2 gas assist, COIL cuts aluminum at approximately the same rate as CO_2 cuts steel. This finding may have important implications for COIL as an excellent laser for aluminum cutting/welding/drilling applications.

COIL and Nd:YAG cut steel at approximately the same rate when using either an inert or an oxygen gas assist. Since the wavelength of COIL and Nd:YAG are roughly the same, this is not a surprising result. However, 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 steel. Since COIL cuts metal faster than CO_2 lasers, and Nd:YAG lasers are presently limited in power level, COIL has considerable potential as a high power (> 5 kW) industrial laser.

Carroll and Rothenflue[19] compared these data with a laser cutting model developed by Kar, Scott and Latham.[17] Using thermophysical data for stainless steel, carbon steel and aluminum, this theory agrees reasonably well with the data. However, there was some divergence between the model and data for low values of $w_k v$. To improve the agreement between the model and data at lower values of $w_k v$, Carroll and Rothenflue[19] added an empirical correction factor to the existing cutting theory; this modification produced excellent agreement with the data. The theory still needs to have a reactive term added to model O_2 gas assist data.

More carbon steel and aluminum data should be taken. The acquisition of more data using a shorter focal length lens arrangement and a beam with fewer transverse modes is desirable. Improvements to the oxygen assist technique should be made and more data taken with an O_2 gas assist. Undoubtedly, much can be learned from existing CO_2 reactive gas assist cutting technology. One possibility is to use an air gas assist with around 1000 kPa (145 psia) plenum pressure. Such a high pressure air assist would provide roughly the same amount of oxygen as used in these tests, but would provide a larger momentum with which to blow molten material out of the cut, as well as increase the convective heat loss; these effects should reduce the amount of reactive melting in the workpiece and improve the quality of the cut. Another possible improvement is the commonly used practice of cutting downwards (rather than horizontally); this allows gravity to help pull molten material out of the cut region.

The results of cladding experiments using a COIL were presented. These experiments coated a stainless steel substrate with a zirconium oxide and aluminum layer. Low Al content in the initial cladding powder mixture produced a crack-free coating with fish-scale-like surface morphology. High Al content in the initial cladding powder mixture produced a relatively smooth surface, but the surface had a few cracks. There was very little dilution of the substrate by the cladding powder mixture. Further studied are needed to understand the effects of Al on the surface morphology and cracks. Oxidation tests are needed to determine the amount of improvement in the oxidation-resistant properties of the substrate.

5. Acknowledgements

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Meet the Authors

Dr. Carroll is a research scientist at the University of Illinois at Urbana-Champaign with a joint appoiontment in the departments of Aeronautical and Astronautical Engineering and Mechanical and Industrial Engineering. His current research primarily focuses on various issues related to the industrialization of chemical lasers; these include technological device improvements and laser materials processing with a COIL.

Dr. Rothenflue is a Captain in the United States Air Force. He received his Bachelor of Science degree from the University of Texas at Arlington in 1987. While serving in the United States Air Force, he earned a Masters and a Ph.D. in Aeronautical Engineering from the Air Force Institute of Technology in 1991 and 1996 respectively. He presently works on materials processing applications with a COIL at the Phillips Laboratory.

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Dr. Latham completed his Ph.D. in Physics in 1976. After being hired by the Air Force to work at the Phillips Laboratory, he studied Optics at the Optical Sciences Center at the University of Arizona. His primary research areas have been laser theory and laser materials interaction. He has analyzed and designed several novel resonant cavities for use with high power lasers. More recently, he has been involved with laser materials processing research as well as serving as an administrator and promoter of cooperative programs at Phillips Laboratory.