Physical and mechanical behaviour of mild steel under a CO_2 laser

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Abstract

In this paper, we investigate the physical and mechanical behavior of mild steel when machined using a CO_2 laser. First, some of the etched mild steel specimens are spray painted and dried. A continuous wave (cw) CO_2 laser beam with an estimated power of 35 Watts is then focused on both the painted and unpainted specimens for a wide range of exposure times. The machinability of the painted and unpainted specimens is observed. Both sets of specimens are then checked for any microstructural changes. It was clear that the unpainted specimens had no visible marks or microstructural changes even after the longest exposure of 1000 seconds. However, it was observed that exposure of the material to the beam had effects on the microstructure of the painted specimens even with as little exposure time as 30 seconds.

Keywords

Keywords: CO_2 laser, microstructure, paint removal, physical and mechanical properties, underlying material.

I. INTRODUCTION

LASERS are employed in a wide range of applications such as in cutting, marking, drilling, heat treatment, cleaning of surfaces and paint removal. This is due to the many benefits associated with the laser technology in terms of geometrical and dimensional accuracy which have proven to be difficult and expensive with conventional machining processes. Generally, metals are not good candidates of laser machining due to their high thermal conductivity and high reflectivity to the infra-red (IR) energy from a CO_2 laser. Painting of metallic surfaces has been used as a way of improving the absorptivity to the CO_2 laser radiation to allow easy laser machining. Physical properties of metals such as thermal conductivity and material viscosity influence quality, productivity, profitability and safety of laser cutting operation [1].

For a particular material, a minimum amount of energy has to be absorbed for the material to be ablated by the laser beam. This absorbed radiation is converted to energy that raises the temperature of the substrate. The input of energy or energy deposition process from a laser beam into the near surface regions of a solid involves electronic excitation and de-excitation within an extremely short period of time [2]–[4]. This means that laser-matter interaction within the near-surface region achieves extreme heating and cooling rates in the range of 10^3 - 10^{10} K/s, while the total deposited energy (typically, 0.110 J/cm^2) is insufficient to significantly affect the temperature of the bulk material. Pulsed lasers or use of assisting gas enable achievement of high cooling rates. This allows the near-surface region to be processed under extreme conditions with little effect on the bulk properties. The resulting temperature profile depends on the deposited energy profile and thermal diffusion rate during laser irradiation. Reflectivity of most metals is high at low beam intensities but much lower at high intensities since this reflectivity reduces with increasing temperatures [5].

The resulting temperature profile depends on the deposited energy profile and thermal diffusion rate during laser irradiation. Only part of the laser power is useful for cutting while the rest is wasted through reflection by the workpiece surface or transmitted through successive partial reflections. Absorption of laser radiation [6] in materials is generally expressed by Beers Lambert Law:

$$I(z) = I_o e^{-\mu z} \tag{1}$$

where $I(z)$ is the laser intensity at depth z, I_o is the incident laser intensity and μ is the absorption coefficient of the material.

Most metal surfaces reflect IR light at 80 % and above at room temperature. The 20 % light is absorbed and converted into heat that initiates melting [7]. The nature of interaction of laser radiation with metal surface depends upon physical and metallurgical properties of the metal and all the process parameters involved. This means that to each kind of material, including its thickness and surface finishing, there will be a different collection of process parameters that will optimize a determined feature of the cutting product. Generally, metals are more difficult to machine using CO_2 laser due to their high reflectivity to this wavelength. However, this does not mean that CO_2 laser machining of metals does not exist.

Michael et al. [8] investigated productivity characteristics of a 4 kW CO_2 laser cutting system for 0.25 inch mild steel. They found that laser cutting operations generally produced regular patterns in the cut surface, known as striations whose severity (frequency and amplitude) had a direct impact on surface quality. Incomplete cuts resulted from low oxygen pressure, deterioration of the focusing lens , and/or trying to cut at a rate exceeding the power rate required for maintaining complete cutting. They controlled some parameters such as feed rate, power, assist gas pressure and laser pulse frequency while the condition of the focusing lens, nozzle gap and assist gas purity remained uncontrolled. They made the following general observations:

- An amount of variation between observations of experimental runs resulting to either the cut surface being very well within the acceptable limits established (Ra. less than 18 μ m), or very poor
- The greater the roughness values were, the wider the variations among the individual measurements became.

Uslan [9] investigated on kerf width variation during a CO_2 laser cutting of mild steel where the influence of laser power and cutting speed variations on the kerf width size was examined. It was found that the power intensity at the workpiece surface significantly influenced the kerf width size. The variation in the power intensity resulted in considerable variation in the kerf size during the cutting, which was more pronounced at lower intensities.

In order to successfully machine hard-to-wear materials, Kelly et al. [10] made innovations in laserassisted-manufacturing (LAM) which combined laser technology with traditional machining methods such as turning and milling. The laser was used as a heat source with the beam focussed on the unmachined section of the workpiece directly in front of the cutting tool as shown in Figure 1. In their

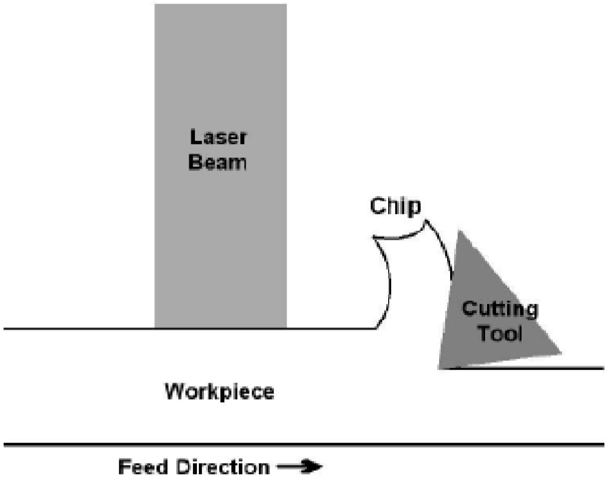


Fig. 1: Laser Assisted Machining (LAM) Principle [10]

work, optimum operating parameters were expected to provide minimum surface roughness, subsurface defects, tool wear, tooling costs, machine time and maximum MRR, precision and accuracy. Preheating the material to be machined softened it resulting to less force required by the conventional tool while cutting. This had the advantage of minimizing tool wear and thus grinding or diamond machining which accounts for about 60-70% of manufacturing cost of the final product. In LAM technique, temperature of the workpiece is very important so that ductile deformation occurs during cutting. However there is to be no melting of the material, heat treating of the bulk workpiece or softening of the cutting tool, as these are all detrimental to the surface integrity of the finished workpiece. For this reason heating should be localized as much as possible to the surface layer of the material to be removed before substantial heat is conducted into the bulk of the workpiece.

When cutting thick plates of mild steel, oxygen (O_2) assist gas was used to take the advantage of the exothermic reaction occurring between iron (Fe) and O_2 at 2240 ^oC before melting starts [7] as shown in Equation 2. The heat power generated in kJ/mol depended on material thickness, O_2 flow rate and feed

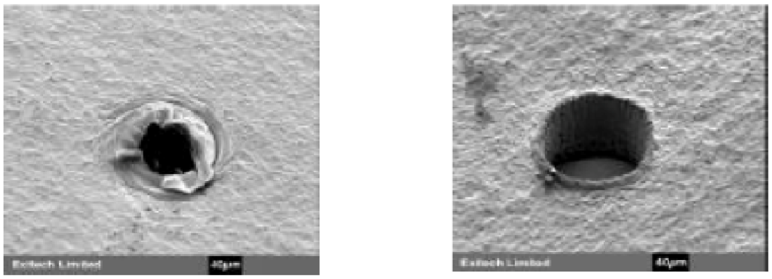
rate.

$$Fe+1/2O_2 \rightarrow FeO+260 \quad (2)$$

Oxygen-assisted laser machining resulted in an exothermic reaction especially with carbon steel and stainless steels allowing higher machining speeds to be achieved. In a related study, David [11] had the aim to determine the maximum speed achievable for a certain material thickness, laser power and with increasingly higher oxygen purity using a CO_2 laser. He found out that the higher oxygen purity resulted in cleaner cuts and better edges quality at high cutting speeds. However, oxygen purity alone does not dictate the speed and cut quality since other factors like laser power and material thickness also play an integral role in the resultant speeds and quality.

Shuja et al. [12] investigated the influence of gas jet velocity in laser heating of a moving steel substrate. Simulation was repeated for three assisting gas jet velocities (100, 10, 1 m/s) and a constant workpiece speed of 0.3 m/s. It was found that the effect of assisting gas jet velocity on the surface temperature was more pronounced in the cooling cycle than in the heating cycle of the laser heating process. The workpiece movement affected the location of the maximum temperature at the surface, which moved away from the initially irradiated spot center in the direction of motion of the workpiece.

Chen [13] investigated the effects of gas composition on CO_2 laser cutting of mild steel. In his research, gas-composition variation and the gas pressure were selected as the dominant factors and their effects on the cut quality investigated, with particular reference to small variations in gas composition. He used gas mixtures composed of oxygen, argon, nitrogen and helium. From the experimental results, it was found that a high purity of oxygen was required for the high-performance CO_2 laser cutting of mild steel. Only a tiny oxygen impurity (1.25%) reduced the maximum cutting speed by 50% for 3 mm thick under low pressure up to 6 bar-inert gas cutting. Laser drilled holes have showed better profiles and geometrical accuracy than traditionally-machined holes as shown in Figure 2.



a) Mechanically-drilled hole b) Laser-drilled hole

Fig. 2: Difference between mechanical and laser drilled holes [14]

II. MATERIALS AND METHOD

A. Preparation of mild steel specimens

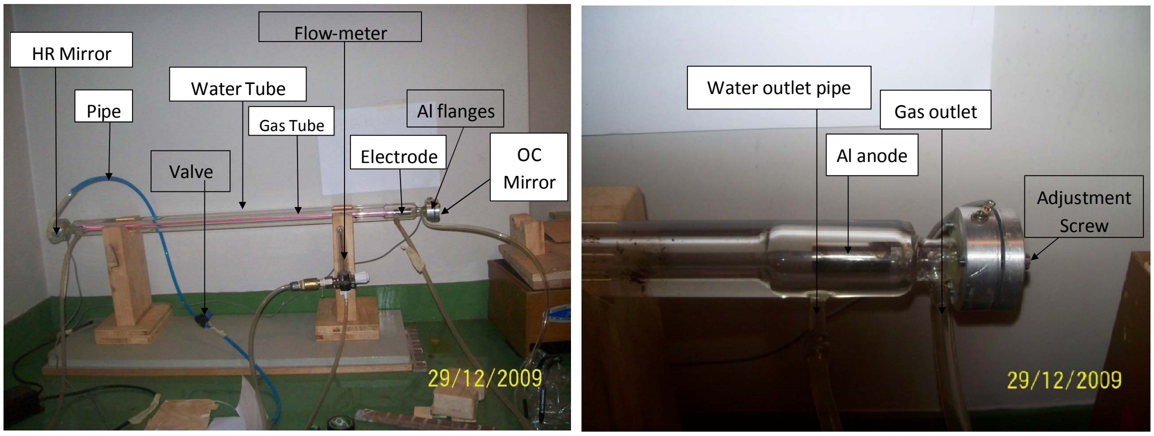
Mild steel specimens were prepared in order to obtain a flat and smooth surface for laser machining. The section to be examined was sawed, then manually filed and surface ground using a universal surface grinder. Samples were mounted using resins and ground using progressively finer SiC waterproof papers. The specimens were then polished using 6 and 1 μm granulation diamond paste and etched in dilute acid (2% Nital= 2ml HNO_3: 98ml Ethanol CH_3CH_2OH). Finally it was washed in alcohol and dried.

B. CO_2 laser generation and delivery

In order to investigate the physical and mechanical behaviour of mild steel under a CO_2 laser beam, the beam was first generated, then delivered from the source to the workpiece using mirrors and focused on the painted mild steel specimens for a range of exposure time and the microstructure observed under a microscope. The laser generation tube with its details is shown in Figure 3. After the laser beam generation, the beam was manipulated through the beam delivery system as shown in Figure 4. The arrows in Figure 4 indicate the laser beam path.

C. Painting of specimens

A thin coating of ABRO^{TM} spray paint was sprayed on the shiny surface of some mild steel samples and left to dry in air. An illustration of the specimen before and after painting is as shown in Figure 5. One of the limitation was that it was not possible to measure the thickness of the paint layers and thus uniformity could not be ascertained.



(a) (b)

Fig. 3: Generation of CO_2 laser

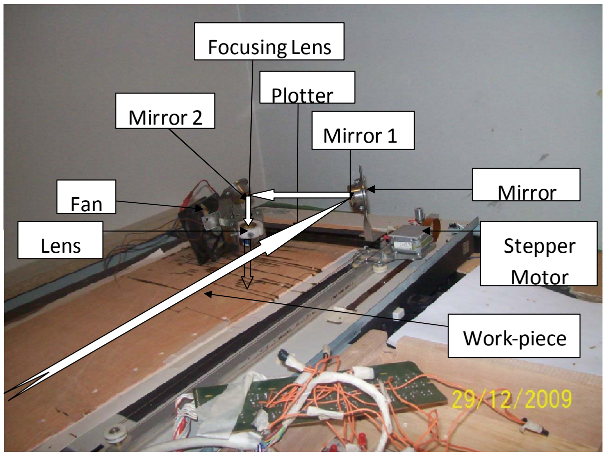


Fig. 4: Laser beam delivery system

D. Laser beam focusing on the workpiece

The aim was to focus the beam on the workpiece so as to concentrate the beam to the minimum spot possible and thus achieve maximum power density which would consequently increase the MRR and reduce the HAZ. The laser beam was always positioned at the surface of the workpiece. This was done by first measuring the workpiece thickness h and adjusting the position of the focusing lens H as shown in Figure 6. The laser beam was focused at a point on the surface of both the painted and unpainted specimens for a defined exposure time. This exposure time was varied from 5 seconds to 500 seconds. With the focal length of the lens as 38 mm, Equation 3 was used where H and h are in mm.

$$H = h+38 \tag{3}$$

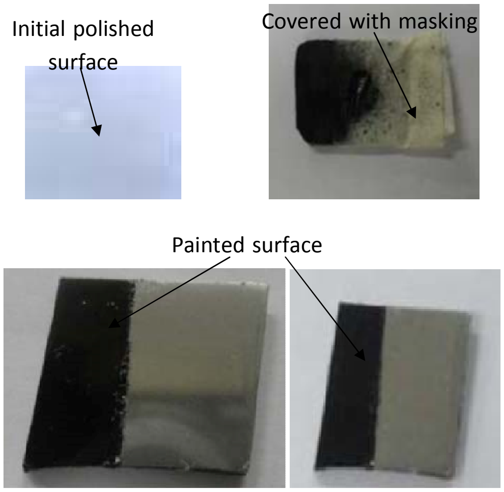


Fig. 5: Coating of the specimens

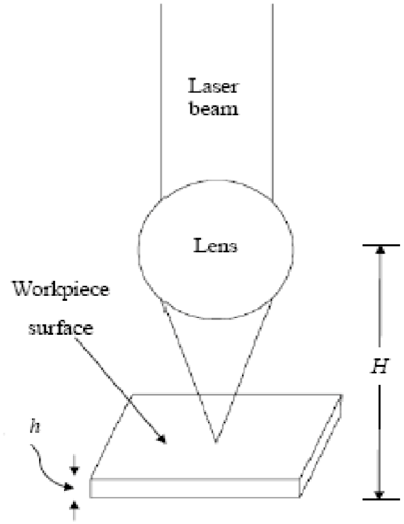


Fig. 6: Positioning of the focusing lens when machining

E. Observation of the microstructures

The microscope used had a resolution of 1.7, eyepiece of 8 times magnification, objective lens magnification of 40, MN11065 model and manufactured by Cooke Traton. The following procedure was used in observing the microstructure of each specimen under the microscope:

1) The specimen was focused under 544 times magnification and the microstructures observed.
2) The eyepiece of the microscope was replaced with the camera, the shutter closed, the photo taken and processed.

To be certain that the observed microstructure after the laser effect had no interference from the paint, a clean painted surface was observed under the microscope with the same magnification and its appearance
was as shown in Figure 7.

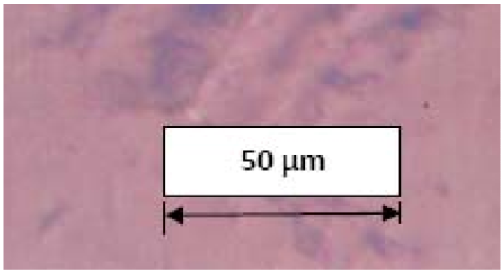


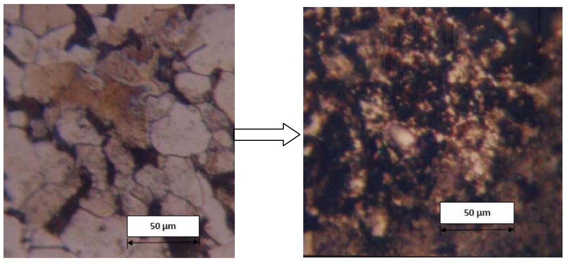
Fig. 7: Appearance of the paint surface under the microscope

III. RESULTS AND DISCUSSION

No visible marks were made on the polished and unpainted surfaces due to the high reflectance of mild steel to CO_2 laser wavelength. However, marks were visible both with the naked eye and under a microscope on the painted surfaces since the paint coating increased the absorption of the laser radiation by reducing reflection. When paper was placed along the reflection path of this beam from the mild steel surface, the paper was evaporated immediately as evidence that the beam must have been reflected rather than absorbed. Plastic placed along the same path was observed to be melting. This is due to the fact that a laser beam is reflected or absorbed depending on the surfaces of the materials.

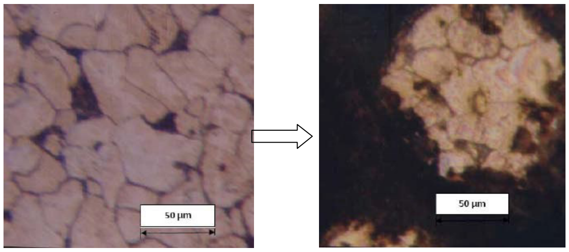
It was observed that all the painted specimens studied had their microstructure altered on exposure while the shiny surfaces had no alteration at all. This shows that painting enhances machinability of mild steel by reducing the reflectivity of the IR energy by metallic surfaces.

Before exposure of the specimens to the laser light, the painted specimens consist of more ferrite (light polygons) and less pearlite (dark, lamellar) structures. On exposure, the diffusion of alloying elements occurs and this changes the ferrite and pearlite ratio in the structure. We can approximately estimate the amount of carbon by the amount of structures such as ferrite, pearlite and cementite. In pure iron, only ferrite exist while at 0.1% and 0.2% carbon steel, pearlite appear at the boundary of ferrite. Pearlite increases still more in place of ferrite with increasing amount of carbon content and the whole domain is occupied by pearlite in 0.8% carbon steel. Mechanical properties such as hardness and tensile strength increase while elongation and impact value decrease with increase in amount of pearlite [24].



i) Before exposure ii) After exposure

(a)



i) Before exposure ii) After exposure

(b)

A. Conclusion

The following conclusions can be drawn from this investigation:

1) Polished surfaces of mild steel have high reflection to the CO_2 laser energy.
2) Laser beam has some physical and mechanical changes on mild steel.
3) Painting improves the surface absorptivity of the mild steel.

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REFERENCES

[1] A. Abramov, Y. Sun and N. Zhou, "High Speed Laser Scoring of Low Coefficient of Thermal Expansion (CTE) Glass Substrates,"

tech. rep., Corning Inc, Sullivan Park, 2007.

[2] M. Leonard, "Laser materials processing," tech. rep., Library of Congress Cataloging, 1996.

[3] James T. Luxon and David E. Parker, "Industrial lasers and their applications.," tech. rep., Prentice-Hal, Inc, 1984.

[4] J. Dutta Majumdar and I. Manna, "Laser processing of materials," *Sadhana*, vol. 28, pp. 495–562, 2003.

[5] K. H. Leong, "Modeling Laser Beam-Rock Interaction," tech. rep., The University of Chicago.

[6] Narendra B. Dahotre, Sandip P. Harimkar, "Laser fabrication and machining of materials," *Springer*, 2008.

[7] C.L. Caristan, "Laser cutting guide for manufacturing," tech. rep., Society of Manufactruring Engineers (SME), 2004.

[8] Michael L. Cadorette and H. Fred Walker, "Characterizing Productivity of a 4kw CO2 Laser Cutting System for 0.25 Mild Steel Using

Central Composite Methodology," *Journal of Industrial Technology*, vol. 22, pp. 1–8, 2006.

[9] I. Uslan, "CO2 laser cutting: kerf width variation during cutting," *Part B: Journal of Engineering Manufacture*, vol. 219, pp. 571–577,

2005.

[10] Kelly Armitage, Syed Masood and Milan Brandt, "Laser Assisted Machining of Hard-to-Wear Materials," tech. rep., Industrial Research

Institute Swinburne (IRIS) in cooperation with Weir Warman Ltd, 2004.

[11] D.Smith, "Gas-assisted laser cutting," tech. rep., Industrial laser solutions for manufacturing, 2000.

[12] S.Z. Shuja and B.S. Yilbas, "The influence of gas jet velocity in laser heating of a moving workpiece case," *Proceedings of the*

Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol. 214, pp. 1059–1078, 2000.

[13] Chen S.L., "The effects of gas composition on the CO2 laser cutting of mild steel," *Journal of materials processing technology*, vol. 73,

pp. 147–159, 1998.

[14] M.C. Gower, "Industrial applications of laser micromachining," *Optics Express*, vol. 7, 2000.

[15] SDI, "Decoating using lasers," tech. rep., 2010.

[16] Graffiti, "Graffiti Removal by Laser," tech. rep., Science & Technology, 2009.

[17] *Efficient TEA CO2 laser based coating removal system*, 2007.

[18] PowerLaser, "High productivity portable laser depainting device," tech. rep., LLC, 2001.

[19] Rui Bordalo, Paulo J. Morais, Helena Gouveia and Christina Young, "Laser Cleaning of Easel Paintings: An Overview," tech. rep.,

Hindawi Publishing Corporation, 2006.

[20] A. Andreotti, M. P. Colombini, A. Nevin, K. Melessanaki, P. Pouli and C. Fotakis, "Multianalytical Study of Laser Pulse Duration Effects in the IR Laser Cleaning ofWall Paintings from theMonumental Cemetery of Pisa," tech. rep., Hindawi Publishing Corporation, 2006.

[21] Katherine Liu and Elsa Garmire, "Paint removal using lasers," tech. rep., Optical Society of America, 1995.

[22] W.G.J. 't Hart, "Paint Stripping Techniques for Composite Aircraft Components," tech. rep., National Aerospace Laboratory NLR,

2003.

[23] Georg Heidelmann, "Surface Cleaning with Laser Technology," tech. rep., Adapt Laser Systems LLC.

[24] Seiichi Ishida, *Standard microstructure-Group of carbon steel-cast iron*. Yamamoto Scientific Tool Labolatory Co. Ltd, 1973.