Surface Morphology and Metallurgical Studies on Gas-Assisted Laser Beam Hybrid Micromachined Steel

Sachin Singh, Subash Babu Matta, and M. Ravi Sankar

Abstract Micromachining with laser is an established technique used in different industries such as aerospace, automobile, electronic and medical industry. Compared with other processes of drilling holes, laser drilling has the ability to drill very precise micro holes with no tool wear. In the present work, an attempt is made to micromachine straight micro holes using the gas-assisted laser machine on 2 mm thickness steel workpieces. Effect of the input parameters such as laser power and assist gas pressure are studied on the output responses viz. entrance hole diameter, exit hole diameter and taper length. Laser-machined hole surface morphology is analyzed with the help of an optical microscope and scanning electron microscope. Surface metallurgical characterization is carried out to differentiate the recast layer, heat-affected zone (HAZ) and conversion layer by the material elemental composition.

Keywords Laser micro-drilling · Gas pressure · Laser power · Hole diameter · Hole taper length

1 Introduction

There are extensive studies for laser drilling in various applications such as aerospace industries, automobile industries, electronic industries, etc. [1]. The conventional drilling, techniques employed often lead to a rough surface, more machining time, non-repeatability, tool wear, low machining rate and inaccurate hole diameter. Laser

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drilling is an inexpensive and flexible alternative to replace conventional hole drilling methods. Almost all the materials such as mild steel, alumina, glass, copper, and composites can be drilled by laser drilling with high accuracy, repeatability and reproducibility [2]. Laser machining is mainly a non-contact type technique eliminating tool wear and also reduces the limitations to shape formation with minimal sub-surface damage. Comparing other commercially available lasers, CO_2 laser has several advantages such as low operating cost, few processing steps, high cutting quality, narrow incision width (general 0.1–0.5 mm), high precision and highly-flexible CNC programming of shapes for engineering prototyping. The CO_2 lasers are available with a wide range of average power, output ranging from a few watts up to over tenth of kilowatts, which helps for processing a wide range of materials. Therefore, CO_2 lasers are used for performing micromachining operations. In today's technological growing world laser micromachining (LμM) is an ideal choice for research and development, prototyping and batch production of novel ideas. Micro-holes are one of the common microfeatures machined by CO_2 lasers [3]. Some of the applications include flat panel displays, hard-disk drives, printers, cameras, cellular phones, photocopiers, PC's, fuel injector nozzles, turbine blades holes and stents. There are many parameters such as laser power, frequency, gas pressure, number of scanning passes, scanning speed, focal point position which affect the hole quality. Proper control of these parameters is required to achieve the desired hole quality.

CO_2 lasers are commonly used for cutting, welding and drilling purposes. Several researchers carried out the experimental study to observe the effect of laser input parameters on cutting quality. Researchers carried out the cutting of aluminum [4], stainless steel [5, 6], high strength steels [7] and inconel [8]. Cutting quality is generally reported in terms of kerf width, edge roughness and the size of the heat-affected zone (HAZ). Wang et al. [9] studied the characteristics of laser welding. Authors welded advanced high strength steels and studied the effect of input process parameters on microstructure and mechanical properties. Hengfu [10] machined the microchannels on polymethylmethacrylate by CO_2 laser. A relationship between laser power, scan velocity, number of passes and microchannel depth was acquired. The influence of CO_2 laser input parameters during micro-drilling of different carbon content steel is studied by Chen et al. [11]. With an objective to obtain a high-quality hole on ceramics with low taper and low spatter deposition, Yan et al. [12] carried out the experimental and numerical study. Some authors also reported the effect of the pulse duration of CO_2 lasers on the drilled hole quality [13, 14]. Thermoplastic polymer was drilled by Masmiati and Philip [15]. Best combination of laser input parameters for improved hole quality in terms of taper and circularity of hole was reported in the study. Hirogaki et al. [16] did an experimental study of drilling blind holes by CO_2 lasers on the printed wiring boards. Nagesh et al. [17] reported the effect of adding carbon nanopowder during the laser drilling. Carbon black dispersed vinylester/glass is drilled by laser. Authors reported that the taper angle is reduced by the addition of carbon black and performing experiments at high laser power. In the recent developments, researchers carried out underwater machining by CO_2 laser. Authors reported that underwater laser machining produces surfaces with reduced substrate defects [18]. Tsai and Li [19] also carried out a similar study on underwater laser machining of LCD glass and alumina. Authors reported that the distance between the two drilled holes underwater is less than that drilled in air. This is due to the reduced microcracking and affected area by heat of the laser underwater.

As found from the literature survey a considerable number of the researchers concentrated their work on CO_2 laser cutting. Few studies were carried out on laser drilling of thermoplastics, glass, ceramics and metals. Still, detailed study is to be done to study the influence of CO_2 laser on the drilled hole quality, recast layer, heat-affected zone, conversion layer and dross. So, in the present investigation, CO_2 laser is used for drilling micro holes in AISI 1040 steel workpieces. Experiments are performed to study the effect of process parameters on hole quality. Scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDX) analysis are conducted to study morphology and elemental composition of the hole surface. From EDX analysis the elemental composition of the recast layer, HAZ and conversion layer are studied.

2 Experimentation

In the following section, the experimental setup, material, input conditions, experimental procedure of laser drilling are described. Various laser input process parameters and their ranges are given in Table 1.

2.1 CO_2 Laser Test Set up

The experiments are conducted on AISI 1040 steel using air-assisted CO_2 laser machine of 2500 W power. The experimental setup showing the laser head and the workpiece is shown in Fig. 1. Oxygen is used as an assist gas in the present work.

2.2 Experimentation

Experiments are conducted to study the effect of input process parameters and to obtain their optimum range for machining of a good quality hole. Experiments are

Table 1 Process parameters and their respective ranges

Input parameter	Range
Gas pressure (MPa)	0.5–0.9
Laser power (W)	1000–1500
Standoff distance (SOD) (mm)	1.000

Fig. 1 Overview of air-assisted CO_2 laser micromachining experimental setup

conducted by varying the input power, gas pressure and using O_2 as assist gases. Hole formation starts from 0.4 MPa but comparable good quality holes are starting from 0.5 MPa. So, 0.5 MPa is chosen as starting gas pressure in present experimental work. Experiments are planned and conducted for five levels. Maximum gas pressure is 0.9 MPa. A full factorial way is adopted for the design of experiments. The experiments are carried out with different combinations of process parameters. The standoff distance (=1 mm) is kept constant so as to keep the focal point minimum. The hole diameter is characterized by SEM and optical microscope.

3 Results and Discussion

3.1 Effect of Laser Power and Gas Pressure on Hole Diameter

The effect of laser drilling parameters laser power and gas pressures on hole entrance and exit diameter are shown in Fig. 2a, b respectively. The entrance hole diameters produced are in the range of 590–1250 μm for gas pressures 0.5–0.9 MPa and powers

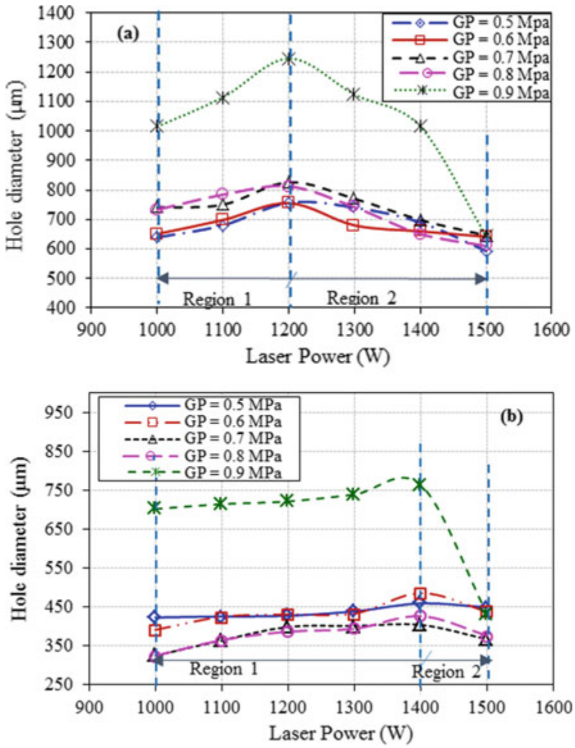


Fig. 2 Effect of laser power on hole diameter for AISI 1040. **a** entrance diameter, **b** exit diameter

1000–1500 W. While, exit diameter of the hole varies from 320 to 765 μm. It can be seen that the entrance and exit hole diameter increases to a threshold value of laser power. The increase in the laser power increases the heat energy given to the material per unit time. This causes the increase in hole diameter throughout the thickness which can be seen in region 1.

Increase in diameter is observed up to the critical point of power, i.e. 1200 and 1400 W for entrance and exit diameters, respectively. Beyond the critical power 1200 and 1400 W the molten material in the melt front re-solidifies around the hole causing shrinkage in the molten material. Due to this phenomenon, the hole diameter stops increasing after the critical laser power which can be seen from region 2.

When very high powers are used spatter deposition takes place due to high melt ejection velocity and insufficient gas pressure. Figure 3 shows SEM images of the laser-drilled holes in AISI 1040 steel plates. These holes are drilled at laser power of 1500 W.

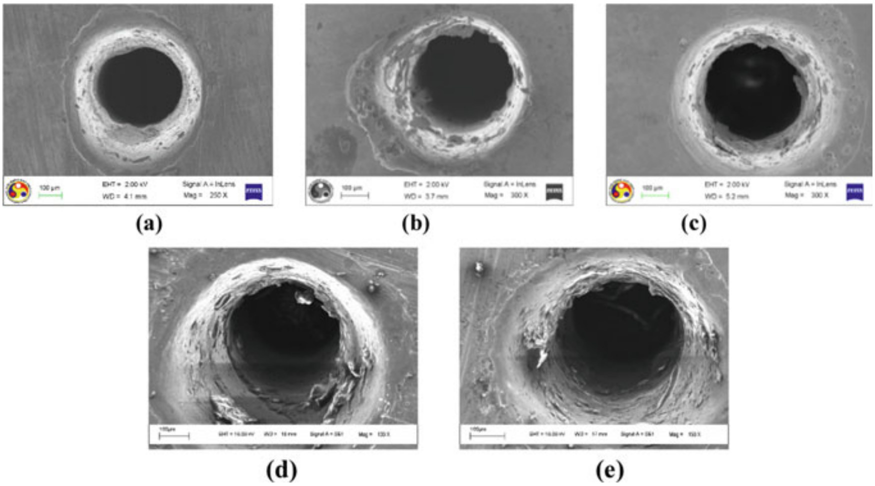


Fig. 3 Surface morphology of the laser micromachined holes at gas pressure. **a** 0.5 MPa, **b** 0.6 MPa, **c** 0.7 MPa, **d** 0.8 MPa and **e** 0.9 MPa

3.2 Effect of Laser Power and Gas Pressure on Hole Taper Length

Hole taper exists when the entrance diameter of hole is larger/smaller than exit diameter. The geometrical quality of the laser drilling can be represented by hole taper length, which is defined as

$$\text{Taper length} = (D - d)/(2) \quad (1)$$

where D is the entrance diameter and d is the exit diameter of the hole.

The relationship between hole taper length and laser power at different gas pressures can be seen from Fig. 4. The taper length decreases with the increase in power. At low powers, the laser intensity is insufficient to penetrate fully into the workpiece. Hence the entrance diameter is more and exit diameter is less when performed with low powers. When the laser powers are high the laser beam has a sufficient amount of energy to penetrate, thus forming a through-hole with less taper. For drilling higher is the laser power, lower the taper length.

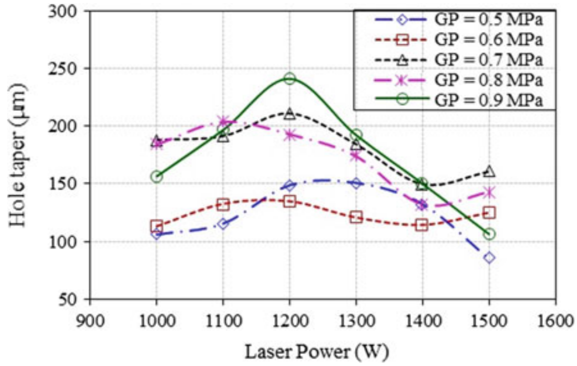


Fig. 4 Effect of laser power on micro hole taper length for AISI 1040

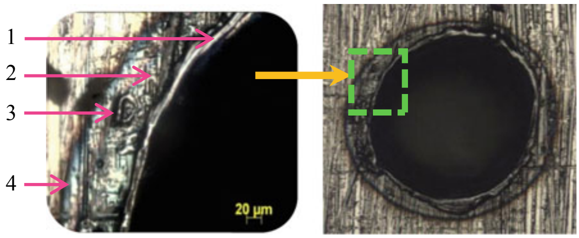


Fig. 5 Optical microscopic image of micromachined hole on AISI 1040 showing hole showing (1) recast layer, (2) heat-affected zone, (3) dross, (4) conversion layer

3.3 Surface Morphology and Elemental Composition Analysis

The surface morphology and the elemental compositional analysis are studied with the help of SEM. Morphology study is carried out of hole top surface which consists of heat-affected zone (HAZ), recast layer, conversion layer and dross (Fig. 5).

Dross is a solid impurity attached to the surface. It is the impurity that remained after solidification of the molten material. Figure 5 shows the image of the hole drilled with power 1500 W and gas pressure 0.7 MPa.

3.4 Elemental Composition of the Surface

The elemental composition of the surface is done with the help of SEM and EDX. It is used to differentiate the recast layer, heat-affected zone (HAZ), conversion layer and dross material by finding the elements in the desired location. In the present work, the EDX analysis is done for a hole drilled with laser power 1300 W and gas pressure 0.6 MPa.

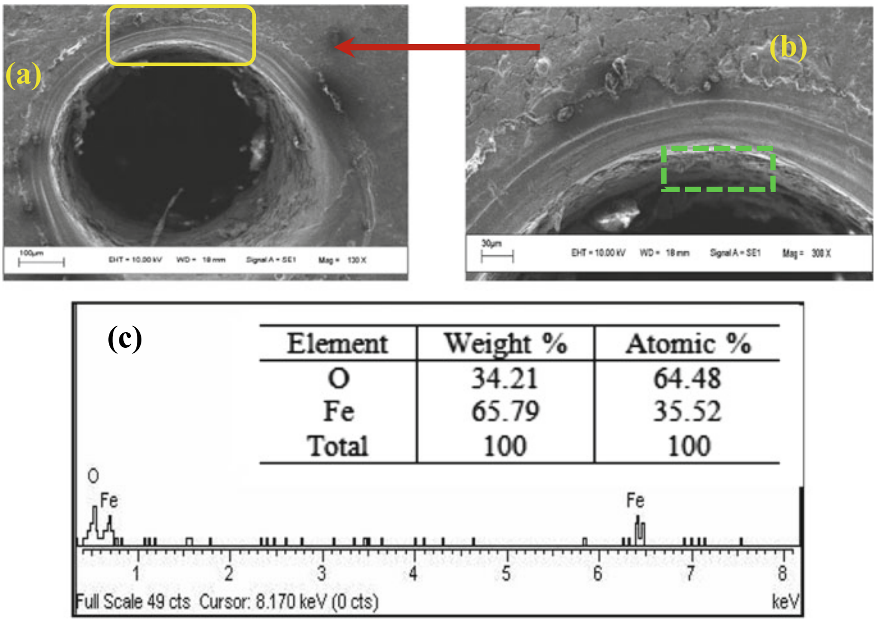
Elemental analysis for recast layer

The recast layer is the re-solidified layer of the molten material which is attached to the surface of the hole. It majorly consists of O_2 and Fe. As the assist gas used is O_2. The SEM image and the location where the EDX is done can be seen from Fig. 6.

From Fig. 6c, it can be seen from the atomic % that the O is twice that of Fe signifying the composition as FeO_2.

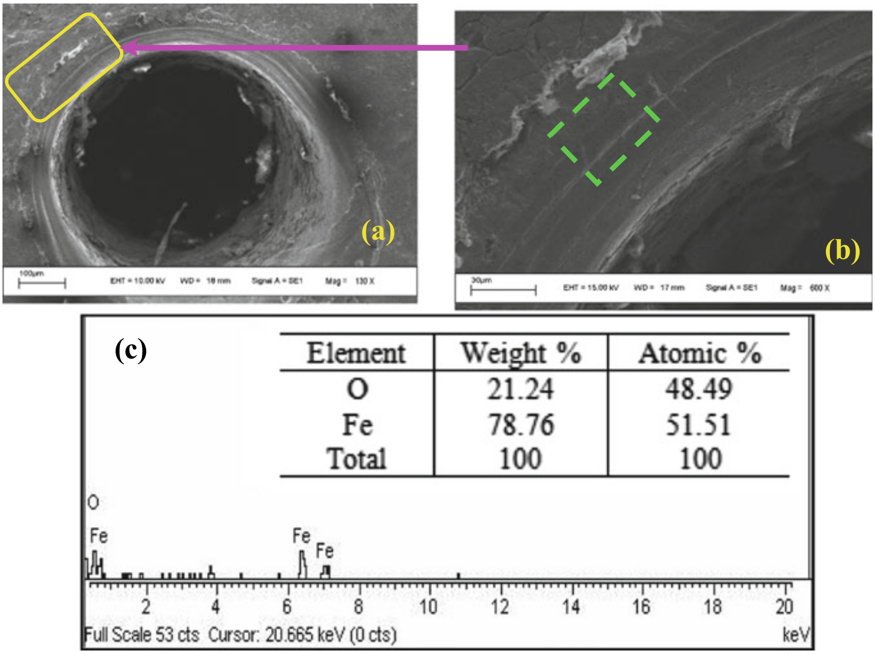
Elemental analysis for heat-affected zone

Heat-affected zone is the layer adjacent to the recast layer. It partially melts due to the melt front produced by the laser beam and grain structure is altered in this region. Figure 7 shows the SEM image of the HAZ. From Fig. 7c, it can be seen from the atomic % that the O is approximately equal to Fe signifying the composition as FeO.



Element	Weight %	Atomic %
O	34.21	64.48
Fe	65.79	35.52
Total	100	100

Fig. 6 **a** Surface morphology of the laser micromachined hole, **b** image showing recast layer and location where the EDX is done and **c** elemental composition showing ranges of Fe and O



Element	Weight %	Atomic %
O	21.24	48.49
Fe	78.76	51.51
Total	100	100

Fig. 7 **a** Surface morphology of the laser-drilled hole on AISI 1040, **b** image showing HAZ and location where the EDX is done and **c** surface metallurgy showing the ranges of Fe and O

Elemental analysis of conversion layer
This is formed due to heat from the melt front. Figure 8 shows the conversion layer where EDX is performed. From the elemental analysis, it can be seen from atomic % (approx.) that the conversion layer consists of Fe and a very small amount of oxygen.

Elemental analysis of dross
Dross is a solid particle attached to the molten material. Figure 9 shows the elemental analysis of dross. From the elemental analysis, it can be seen from atomic % (approx.) that the dross consists of three parts of oxygen and one part of Fe approximately. Thus, it signifies that it contains FeO_3.

4 Conclusion

In this paper, CO_2 laser drilling of AISI 1040 steel plates is successfully demonstrated and studied.

1 The minimum entrance diameter of hole produced in this work is 593.1 μm at 0.5 MPa gas pressure and 1500 W laser power.

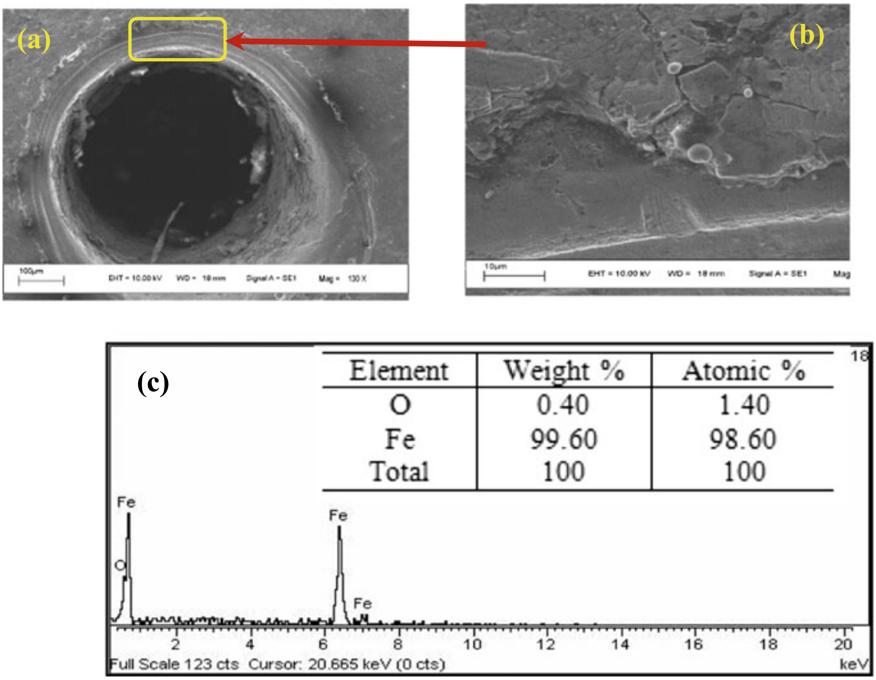
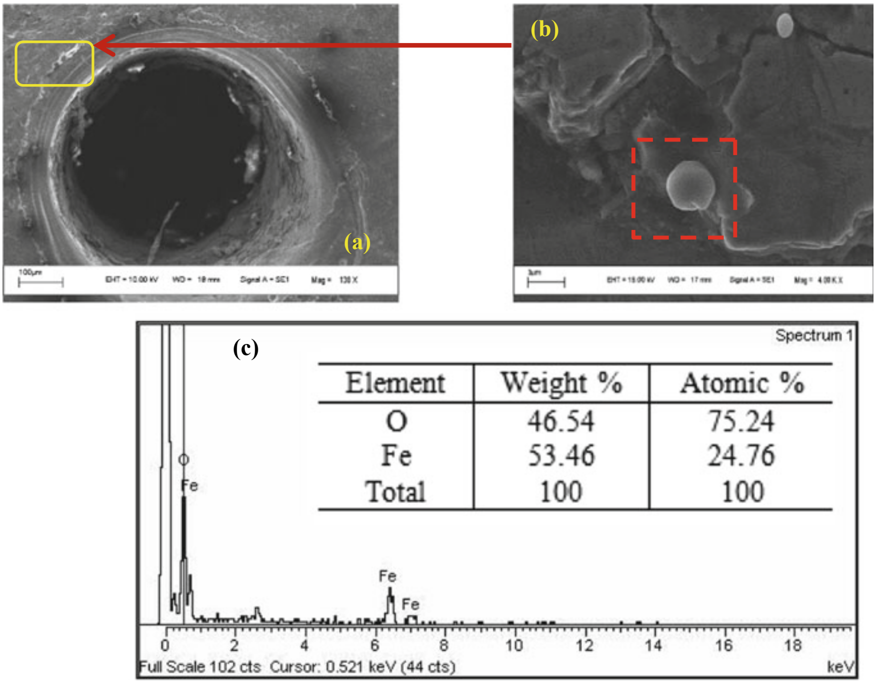


Fig. 8 **a** Surface morphology of the laser-drilled hole, **b** image showing C.L and location where the EDX is done and **c** surface metallurgy showing the ranges of Fe and O

2. It is also observed that the taper length decrease with an increase in power. The hole with a minimum taper length of 85.06 µm is obtained at 0.5 MPa gas pressure and 1500 W laser power.
3. Different zones of the machined surface, i.e. layers recast layer, HAZ and conversion layer are differentiated with the help of elemental analysis.
4. The obtained elemental compositions are FeO_2 in the recast layer, FeO in HAZ and Fe in conversion layer. The dross is also studied and the composition of the dross obtained is FeO_3.



Element	Weight %	Atomic %
O	46.54	75.24
Fe	53.46	24.76
Total	100	100

Fig. 9 **a** Surface morphology of the laser-drilled hole, **b** location showing where the EDX is done and **c** surface metallurgy showing the ranges of Fe and O

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