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High-speed laser micro-hole drilling of 1 mm thick C263 Nickel alloy

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Abstract

Over the last few years, there has been an accelerated push to advance hydrogen electrolysers and fuel cell technology, with *green hydrogen* identified as a viable means to contribute to the decarbonisation of many instrumental industries. Laser drilling is an enabling technology to produce porous structures and micro-holes in various critical components used throughout the construction of modern hydrogen electrolysers. To commercialise micro-hole drilling in this area it is necessary to develop processing capabilities that permit processing at high speeds and throughput rates in various materials.

This paper investigates the capabilities of creating micro-holes using a single mode fibre laser in 1 mm thick C263 Nickel alloy, a common material used in hydrogen electrolysers. A single-mode fibre laser is used in combination with a nozzle-based coaxial processing gas to produce the holes. Experimental trials were performed to understand the effect of peak power and pulse duration on the size and quality of single pulse laser drilled micro-holes. Micro-holes with average diameter less than 90 µm were produced at a rate of approximately 185 holes per second whilst achieving a high level of consistency.

Keywords: Laser micro-hole drilling, hydrogen, electrolyzer, fuel cell

1. Introduction

Over recent years, numerous industries have committed to developing low-carbon hydrogen infrastructure to support the effort to reduce global carbon emissions. The production of low-cost green hydrogen will be

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most impactful in decarbonising "hard-to-abate" industries that are challenging to electrify, such as aerospace, shipping, chemicals and materials production. A clear solution to achieve green hydrogen production is to extract hydrogen gas from water via electrolysis, powered using only renewable energy sources. At present, Alkaline Electrolysis Cells (AEC) and Proton Exchange Membrane (PEM) are the leading electrolysis technologies. Significant research and development have been undertaken in the efforts to improve the electrolysers efficiency, acquisition and operating costs, and use of more standard materials in their construction.

Porous structures are critical elements in hydrogen electrolysers, with these components ensuring the proper functionality of the cells. Recent studies in this area have focused on the use of micro-holes to improve the efficiency of hydrogen electrolysers by improving water management (Geiger et al., 2022), gas bubble saturation (Lee et al., 2020) and increasing activation sites (Kang et al., 2019). Laser drilling is a high-potential enabling technology that is increasingly used in the manufacture of porous structures and micro-perforations for various components of PEM and AEC electrolysers. In recent examples, Geigeret et al. and Alrashidi et al. independently used short and ultra-short, pulsed lasers to introduce micro-holes and perforations from 30 – 500 µm diameter in various diffusion media (Alrashidi et al., 2021) and Wen et al. showed the use of laser drilling for the manufacture of specialist gas diffusion layers which exhibit increased anti-flooding capacity (Wen et al., 2022).

Porous high-temperature nickel alloys of few millimetres in thickness, have been extensively used as the material in electrodes of AEC electrolysers due to its high intrinsic activity (Brauns et al., 2021; Lee et al., 2021). Of particular interest is zero-gap AEC electrolyser designs. This construction minimises the ohmic resistance across the cell using porous nickel electrodes that are separated by a thin diaphragm material. These electrodes commonly take the form of perforated plates (Jiang et al., 2020), mesh (Zayat et al., 2021) and foam (Lee et al., 2020). The benefits of the porosity have been found to greatly increases the active exposed area and encourages the removal of entrapped bubbles, promoting a higher efficiency of the hydrogen production process (Wang et al., 2017; Zhang et al., 2015; Rossi et al., 2023).

It is evident of the increasing demand for the ability to fabricate micro-holes with consistent geometry and quality through materials of 1 – 2 mm in thickness has increased in not only the hydrogen sector but particularly within the aerospace and other energy sectors. For example, micro-holes (diameter 50-100 µm) employed across the leading edge of aircraft wings and tailplanes have been shown to reduce the drag forces induced by boundary layer suction during flight, aiding in improving the aircraft fuel efficiency. Aero-engine efficiency can also be significantly increased using components containing a high density of micro-holes (hole diameters of ~100-200 µm at 100 holes/cm^2) (Stephen et al., 2014).

Control of material melting, and heat propagation, is critical in the micro-hole drilling process (Marimuthu et al., 2019). As this directly relates to the laser pulse duration, short and ultra-short pulse lasers have been the main focus of research in this area to date. However, these lasers have low productivity when machining thicker materials that are often used in many industrial applications. To enable industrialization across a wider range of applications, much higher productivity is essential. Stephen et al. and Uchtmann et al. both demonstrated using a single-mode laser to drill through titanium, obtaining hole geometries below 100 µm, with high throughput rates (Uchtmann et al.,2017).

This research investigates the capabilities of using Single Pulse Micro-Hole Drilling (SPMHD) for high throughput micro-hole drilling of 1 mm thick C263 nickel alloy – a material commonly used within hydrogen electrolysers.

2. Experimental methodology

An Innolas system fitted with an IPG 1070 nm YLR-2000-SM continuous wave laser source was used for this work. This has a peak power of 2 kW, a minimum pulse duration of 10 µs and a modulation rate of up to 50 kHz. The fibre core diameter is 14 µm and it has a collimator and focus lens distance of 150 mm each, resulting in a theoretical spot size of 14 µm with a Gaussian shape and an M2 of 1.1. The focal position was maintained on the upper surface of the target material. The processing gas was argon which was supplied coaxially through a 1 mm diameter nozzle and resulted in the application of approximately 4 bar of pressure to the target surface. This setup was used to drill holes through a 1 mm thick C263 Nickel alloy (EN 2.4650).

Only single laser shot drilling was considered in this investigation to maximise high-productivity drilling. Laser peak power and pulse duration were optimised to suitable parameter combinations that could perforate the sheet of Nickel alloy. The laser peak power and pulse duration were varied to find the limits of the processing window within the constraints of hole diameter, the quantity of material and drilling rate. This will enable the identification of the ideal parameter combination needed to ensure a highly repeatable hole-drilling process whilst targeting rapid production of sub-100 µm diameter holes.

For each parameter set, a grid of 9 holes was drilled. The drilled holes entrances and exits were examined for size and quality using an optical microscope and hole taper was calculated based on the averaged measured entrance and exit hole diameters. Following the identification of the optimal parameter set, trials were performed to identify the maximum hole production rate.

3. Results

The effects of the peak laser power and pulse duration on the average hole diameter and hole taper angle are shown in Figure 1. The hole diameter was taken as the overall average of the measured entrance and exit hole sizes which were each determined as the average of four individually measured holes. For all the tested pulse durations, a minimum peak power of 1 kW per pulse was required to cleanly form the holes in a single shot. The holes did not break through the thickness of the sheet at power settings of 0.5 kW, whilst at 0.75 kW, the holes had fully formed but were extensively clogged with resolidified material, thus these points have not been shown in Figure 1.a. All holes were positively tapered (the entrance hole being larger than the exit hole) as shown in Figure 1.b., with the lowest peak power of 1 kW resulting in the straightest holes for all pulse durations.

Figure 2 shows a measure of the influence of peak power and pulse duration on producing consistent unobstructed micro-holes. For each parameter combination, a minimum of one-hundred holes were imaged to identify an occurrence of an obstruction in the bore of the hole by either recast material or a build-up of dross on the exit surface. Increasing peak power and pulse duration greatly improved the consistency of the induced holes. Above 80% unobstructed holes were achieved with a parameter combination of 1 kW and 0.3 ms. This parameter set was identified as the most viable combination as it resulted in an average hole diameter of approximately 86 µm, the lowest hole taper angle and a suitable throughput rate that would only require minimal amounts of component post-processing.

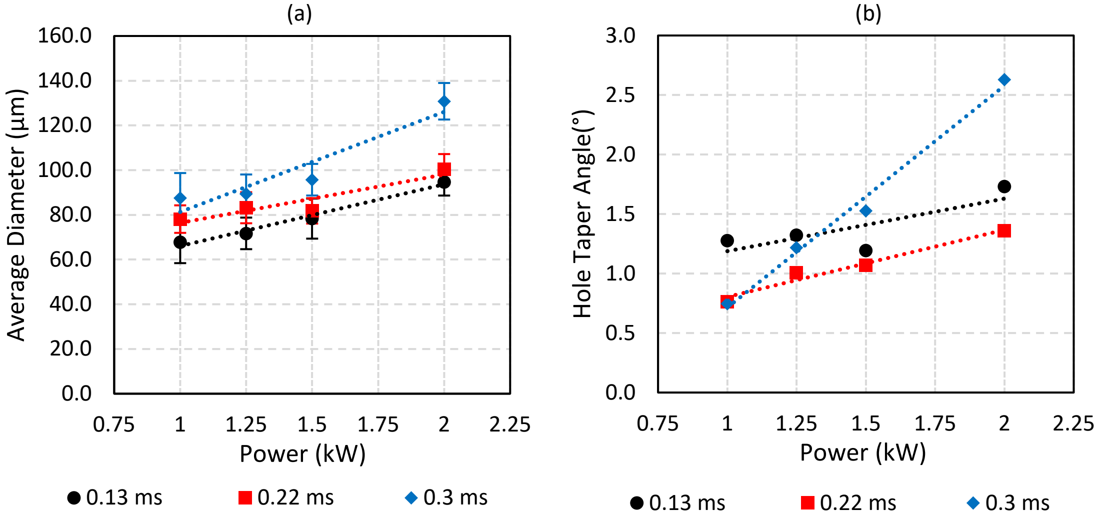

Fig. 1. Influence of peak power and pulse duration on (a) average hole diameter and (b) hole taper angle

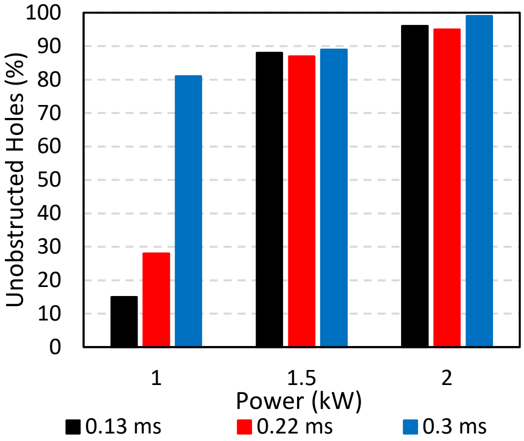

Fig. 2. Influence of peak power and pulse duration on hole clogging

Figure 3.a-d provides an optical assessment of the general quality of the micro-holes produced with a single laser pulse of 0.3 ms and 1 kW. Figure 3.a. and b. indicated that some drilling features such as surface spatter and dross occurred during the formation of the holes. Small amounts of surface spatter surrounded all the drilled holes. A Heat-Affected Zone (HAZ) was also evident in the holes and was most prevalent on the exit surface of the target material. Some form of HAZ is expected with this regime of long pulse drilling as the material removal mechanism is dominated by melting. Figure 3.c. shows an array of micro-holes that are equally spaced at 0.5 mm and generated at a rate of approximately 188 holes/s. Most of the holes were unobstructed through the bore of the hole and are approximately equivalent in hole size. Resolidified recast material was the primary cause of the hole clogging. Figure 3.d provides an example of a cross-section of a row of holes and particularly a single hole.

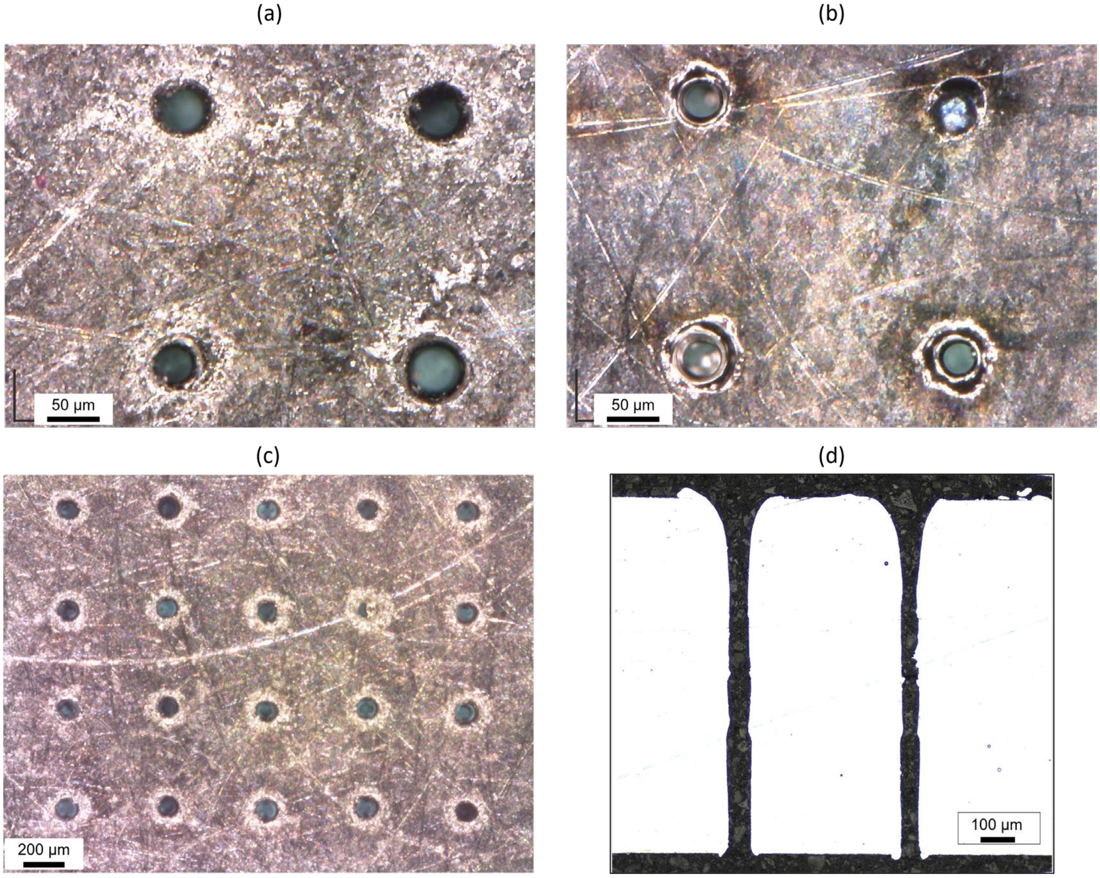

Fig. 3. Drilled micro hole quality at 0.3 ms and 1 kW , (a) laser entrance surface, (b) laser exit surface, (c) example of an array of micro-holes evenly spaced at 0.5 mm, and (d) cross-section along a row of micro-holes

4. Conclusion

In this paper, an experimental investigation was conducted to characterise the ability to laser drill micro-holes in 1 mm thick C263 Nickel alloy in a single pulse. It was concluded that an increase in the laser peak power and pulse duration increased the diameter of the holes and significantly reduced the amount of hole clogging. Drilling rates of approximately 185 holes per second were achieved, demonstrating the potential value of laser micro-hole drilling for high-production throughput rates of vital porous components for hydrogen applications.

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