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# Investigation of a novel hybrid process of laser drilling assisted with jet electrochemical machining

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ABSTRACT

Recast layer and spatter are two inherent defects commonly associated with holes produced with laser drilling. This paper reports a novel hybrid process of laser drilling assisted with jet electrochemical machining (JECM-LD) that aims to minimize such defects and improve the quality of laser-drilled holes. The process based on the application of a jet electrolyte, being aligned coaxially with the focused laser beam, on the workpiece surface during laser drilling. The effect of the jet electrolyte mainly is an electrochemical reaction with materials. The jet electrolyte also cools the workpiece and transports debris during the process. On the basis of a measurement of laser attenuation in electrolyte, an experimental apparatus system is made and JECM-LD experiments have been performed on 0.5-mm-thick 321S20 stainless steel with two lasers at wavelength of 1064 and 532 nm. It is shown that recast layer and spatter have been effectively reduced during the JECM-LD compared with laser drilling in ambient atmosphere conditions.



## 1. Introduction

Laser drilling is a hole-making technique that utilizes the laser beam's capability of being focused to a small spot at power densities sufficient to melt and vaporize the material, which can produce high aspect ratio holes in a variety of metallic materials at very high speed. The unique benefits of the laser drilling technique have made it widely useful in the industry. However, laser-drilled holes are typically associated with a number of inherent defects such as recast layer and spatter. These inherent problems of laser-drilled holes are likely to limit the extent of industrial application of the process.

In view of this, scientist and engineers have been looking for ways of reducing or eliminating the recast layer and spatter during laser drilling. Many prior studies focused on optimizing the laser parameters (e.g., pulse energy, pulse duration, laser wavelength, peak power, and pulse repetition rate), the focal position, the type and pressure of the assist gas [1–10]. Bandyopadhyay et al. used the Taguchi experimental design method to optimize the process parameters of Nd:YAG laser drilling of IN718 and Ti-6Al-4V sheets [1]. The results indicated that the lower level settings for focal position, pulse duration and pulse energy lead to very significant improvements with respect to hole quality attributes of interest such as spatter and recast. Yilbas used statistical approach to test the significance level of the factors that affect the laser-drilled holes' quality and found resolidified material reduces with a reduction in the pulse length for titanium [2]. The effect of process parameters on spatter deposition was investigated by Low et al. [3] and the main conclusion was that short pulse widths, low peak powers and higher pulse frequencies generally resulted in smaller areas of spatter deposition. O'Neill et al. investigated the nanosecond time period Nd:YAG laser drilling of copper, aluminum and M2 tool steel at 1064, 532 and 355 nm wavelengths [4–6]. The results showed the least amount of recast occurring at the highest intensities for the three wavelengths. Khan et al. report on hole quality for nanosecond laser percussion drilling of 200-μm-thick 316L stainless steel performed with micro supersonic gas jets. Their experiments showed that drilling with the air assist-gas jets from the 200 μm nozzle produced the least amount of recast [7]. Some works have shown that ultrashort lasers are good tools for direct ablative microstructuring of solid materials [8–10], the use of femtosecond laser drilling has been shown to reduce the size of recast due to ultrashort beam/material time.

Besides optimizing the laser parameters, other ways such as changing the environment of laser drilling and combining other machining methods with laser drilling were used. Underwater laser processing provided a solution to some the problems of laser machining in air and other gases. The convection-induced fluid motion was observed to aid in the transportation of debris away from the material surface. The liquid environment had the advantage of completely preventing charring and reduction of

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spatter deposition [11,12]. Low et al. managed to produce spatter-free drilling for closely spaced holes by using an anti-spatter coating [13]. The method was based on the application of a specially developed anti-spatter composite coating (ASCC), on the workpiece surface prior to laser percussion drilling. Lau et al. developed a novel technique of ultrasonic-aided laser drilling to improve the overall quality of laser-drilled holes [14]. Li et al. reported a novel technique of chemical-assisted laser machining that aims to minimize recast [15]. The chemical-assisted laser machining process, involving laser processing within a salt solution, was demonstrated that recast has been significantly reduced for both milling and drilling of stainless steel material.

This paper presents a novel hybrid process of laser drilling assisted with jet electrochemical machining (JECM-LD). The process combines the advantages of laser drilling with those of jet electrochemical machining. It has been shown that the process quality can be significantly improved with minimizing the recast and spatter.

## 2. Process principles

Laser drilling is based on thermal mechanisms. The process involves focusing a high-intensity, coherent light beam onto the workpiece surface to produce sufficient power densities to melt and even vaporize the material. Recast layer and spatter are two inherent defects associated with laser-drilled holes. Recast layer is formed by the resolidification of the melt on the walls of the hole. Spatter is the ejected molten or vaporized material that is not completely ejected but resolidifies and adheres around the periphery of the hole.

JECM-LD is different to laser drilling. It combines two different sources of energy simultaneously: energy of photons (laser drilling) and energy of ions (ECM). The main aim of combining a jet electrolyte with laser beam is to obtain high process quality by reducing the recast layer and spatter produced in laser drilling. The jet electrolyte is aligned coaxially with a focused laser beam and creates a noncontact tool-electrode. The focused laser beam and the jet electrolyte are acting on the same surface of workpiece synchronously. In the course of JECM-LD, material is removed mainly by laser drilling and the defects are overcome by the effect of jet electrolyte which consists of effective cooling to workpiece, transporting debris and electrochemical reaction with materials. Fig. 1 illustrates the principles of JECM-LD.

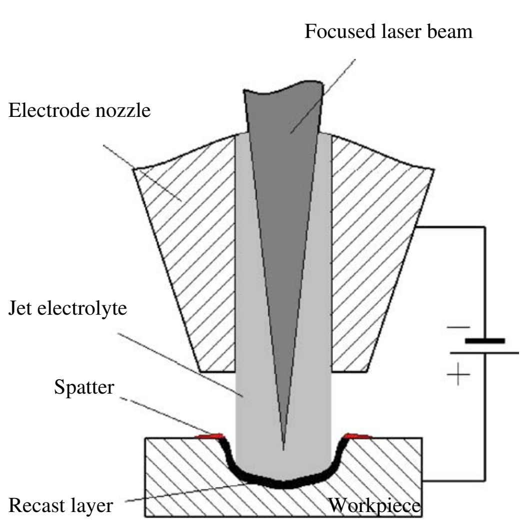


**Fig. 1.** Principle scheme of JECM-LD.

## 3. Measurement of laser attenuation in electrolyte

JECM-LD aligns a jet electrolyte coaxially with a laser beam. The laser beam needs to transmit in the jet electrolyte before being focused on the machining area. Electrolyte is a neutral salt solution, which is attenuable to laser energy by absorption and scattering. The property of laser attenuation in electrolyte is the key factor of JECM-LD.

### 3.1. Theoretical background

Electrolyte is a neutral salt solution with the solute of sodium salt and the solvent of pure water. The solution has a number of particles such as water molecules, metallic ions and suspended matter. These particles have significant effects on the laser attenuation in the electrolyte with absorption and scattering. The total attenuation coefficient $\mu(\lambda)$ of solution is given by [16]

$$I_x(\lambda) = I_0(\lambda)\exp[-\mu(\lambda)x] \tag{1}$$

where $I_0(\lambda)$ is the intensity at the source and $I_x(\lambda)$ is the intensity after transmitting a distance $x$ in solution. The total attenuation coefficient is the sum of the absorption and scattering coefficients. In terms of the absorption coefficient $\alpha(\lambda)$ and the total scattering coefficient $\beta(\lambda)$, $\mu(\lambda)$ can been written as

$$\mu(\lambda) = \alpha(\lambda) + \beta(\lambda) \tag{2}$$

The absorption coefficient is correlative with the refraction of solution. The index of refraction $n(\lambda)$ and the extinction coefficient $k(\lambda)$ of solution are, respectively. The real and imaginary parts of its spectral complex refractive index are written as [17]

$$\vec{n}(\lambda) = n(\lambda) - ik(\lambda) \tag{3}$$

The absorption coefficient $\alpha(\lambda)$ is determined by $k(\lambda)$ and the expression is given by

$$\alpha(\lambda) = 4\pi k(\lambda)/\lambda \tag{4}$$

The total scattering coefficient includes two parts of Rayleigh scattering coefficient $\beta_R(\lambda)$ and Mie scattering coefficient $\beta_M(\lambda)$, which can be written as

$$\beta(\lambda) = \beta_R(\lambda) + \beta_M(\lambda) \tag{5}$$

The scattering coefficient is determined by the radius of the particles in solution. A dimensionless parameter $q(q = 2\pi R/\lambda)$ is used as token of particle size. When $q<0.1$, the scattering is Rayleigh scattering, contrariwise, which is Mie scattering. The electrolyte of this work is an industrial reagent of sodium chloride or sodium nitrate. The electrolyte has suspended particles of different sizes (radius: 5–10 μm) resulting from undissolved matter involved in the industrial reagent. With the higher concentration, the solution has more suspended particles and the effect of scattering is more evident. So the laser attenuation in electrolyte is directly affected by the concentration of solution. The temperature of solution is also a factor to influence the attenuation coefficient. Here two parameters $\Psi_C$ and $\Psi_T$ are used to represent the influence of the concentration and temperature, then Eq. (1) can be deduced as a new expression

$$\begin{aligned} I_x(\lambda) = I_0(\lambda)\exp\{-[\alpha(\lambda) + \beta_M(\lambda) \\ + \Psi_C(C - C_0) + \Psi_T(T - T_0)]x\} \end{aligned} \tag{6}$$

### 3.2. Measurement and results

A measurement of laser attenuation in electrolyte has been carried out based on the theoretical analysis mentioned above. The laser systems used in the measurement are a CW