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# Performance optimization of water-jet assisted underwater laser cutting of AISI 304 stainless steel sheet

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Recent development of water-jet assisted underwater laser cutting has shown some advantages over the gas assisted underwater laser cutting, as it produces much less turbulence, gas bubble and aerosols, resulting in a more gentle process. However, this process has relatively low efficiency due to different losses in water. Scattering is reported to be a dominant loss mechanism, which depends on the growth of vapor layer at cut front and its removal by water-jet. Present study reports improvement in process efficiency by reducing the scattering loss using modulated laser power. Judicious control of laser pulse on- and off-time could improve process efficiency through restricting the vapor growth and its effective removal by water-jet within the laser on- and off-time, respectively. Effects of average laser power, duty cycle and modulation frequency on specific energy are studied to get an operating zone for maximum efficiency. Next, the variation in laser cut quality with different process parameters are studied within this operating zone using Design of experiment (DOE). Response surface methodology (RSM) is used by implementing three level Box-Behnken design to optimize the variation in cut quality, and to find out the optimal process parameters for desired quality. Various phenomena and material removal mechanism involved in this process are also discussed.



## 1. Introduction

Laser processing in the presence of water has been studied since 1970s and now the water-assisted laser cutting, drilling, shock peening and surface cleaning from particulate contamination are finding commercial applications. Underwater laser processing, *viz.* cutting, welding, cladding, and shock peening are often used in the maintenance, repairing and dismantling of nuclear reactor components. Cutting of thin sheet metal in water environment is advantageous due to enhanced cooling in water, which reduces thermal damage. There are different techniques of water assisted or underwater laser cutting. Synova S.A. Switzerland [1] has pioneered and patented water micro-jet guided laser cutting technology, where the laser beam is guided through a high speed water micro-jet. This technique facilitates a long working distance and also reduces thermal and mechanical damages, dross attachment in cutting thin metal sheets, ceramic materials etc. [2,3]. Muhammad et al. [4,5] reported profile cutting of thin tubes of nitinol and 316 L stainless steel with wall thickness less than 200 μm, used for medical application, in dry and wet environment. They reported an improvement of cut quality in terms of heat affected zone (HAZ), kerf width, surface roughness and dross deposition in wet condition, and also eliminating the back wall damage. More recently, Tangwarodomnukun et al. [6,7] developed a hybrid laser water-jet ablation technique, providing a side water-jet to create a thin film of water over the work-piece surface, which enhanced the rate of material removal and also minimize thermal damages. However, in all these techniques, the work-piece thickness is limited up to some 100 s of micron due to insufficient shear force on melt pool.

Chida et al. [8] developed a gas-assisted underwater laser cutting process to cut thick steel plates for application in nuclear industry, wherein high pressure gas jet produces a dry condition in the laser cutting zone and also removes molten material from the cut kerf. They reported cutting of 14 mm thick steel plate with minimum dross using an Nd:YAG laser of 4 kW power. Based on this technique Jain et al. [9] reported cutting of 4.2 mm thick zircaloy pressure tubes and up to 6 mm thick steel plates using a fiber-coupled 250 W average power pulsed Nd:YAG laser. Kruusing [10] presented an exhaustive review of various schemes of gas-assisted and water-assisted underwater laser cutting processes; and described in detail the underwater cutting of nuclear fuel rods with high power $CO_2$ and Nd:YAG lasers. However, the use of assist gas inside water produces gas bubble and aerosols, which may carry some amount of radioactive particles in case of cutting

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radioactive components, resulting in contamination of the surrounding atmosphere.

Recently Mullick et al. [11] developed an underwater laser cutting process where they used a co-axial high speed water-jet as an assist fluid instead of gas. They demonstrated severing of stainless steel sheet of 1.5 mm thickness at a maximum cutting speed of 1400 mm/min using an Yb-Fiber laser at 1800 W power with coaxial water-jet assist at 15–20 m/s speed. This underwater laser cutting process could be attractive in nuclear industries for cutting of radioactive components, as the process is much gentle in nature and produces very little turbulence and aerosols compared to gas-assisted underwater laser cutting process [11]. However, the process has a relatively low overall efficiency due to the loss of laser power in water through different mechanisms. The main mechanisms are the absorption of laser radiation in water, scattering of laser beam by water vapor formed at laser-workpiece-water interaction zone, and convective heat transfer from hot metal surface to flowing water-jet [11–13]. Previous studies reported that the scattering of laser radiation causes maximum loss of laser power [11,13]. The magnitude of loss depended on the growth of vapor plasma and its removal by water-jet [13]. Scattering loss could be minimized by employing modulated laser power of proper laser on- and off- time, thereby restricting the growth of vapor layer during the small laser on-time and effectively removing the vapor layer by the high speed water-jet during laser off-time [13]. This in turn could improve the process efficiency. However, a detailed investigation of the variation in scattering loss and process efficiency in pulsed mode operation has not been reported. The current study investigates the effect of laser modulation frequency, duty cycle and average power on the process efficiency and attempts to determine an optimum processing zone for good cut quality with the high process efficiency.

The quality based study has been carried out implementing design of experiment (DOE) using response surface methodology (RSM) to determine the dependency of different quality factors on various process parameters. Different process parameters considered are the laser power, cutting speed, water-jet speed, laser modulation frequency and duty cycle, whereas the output quality factors are the ratio of top to bottom kerf widths, average dross area at the bottom edge and surface quality. The analysis also provides a better understanding about the material removal mechanism, and its dependence on process parameters under different modes of operation.

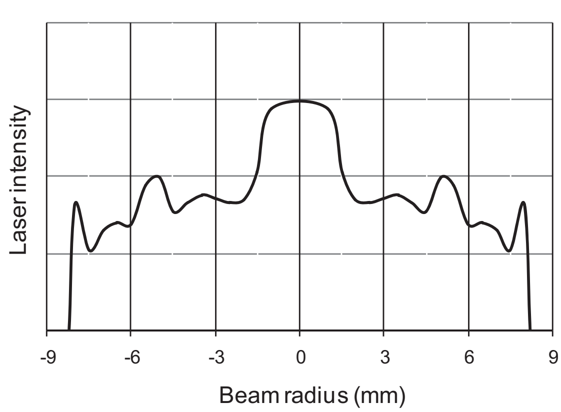


**Fig. 1.** Laser beam intensity profile of the 2 kW Yb-Fiber laser [14].

## 2. Experimental details

In the current study a 2 kW Yb-Fiber laser of 1.07 μm wavelength has been used, which provides a collimated beam of ~16 mm diameter at the output end of its optical fiber beam delivery system. The intensity distribution of the collimated laser beam is shown in Fig. 1 [14]. This is non-uniform having a relatively high intensity central peak surrounded by two annular rings of lower intensities. Though the intensity distribution of the focused beam at focal plane could not be experimentally measured with the available device due to high intensity, the imprint of the focused beam on metal sheet showed a central high peak and a relatively low intensity annular ring. The laser beam is coupled to an in-house developed underwater cutting head. In the current design of underwater cutting head the collimated laser beam is focused in water with the help of a pair of plano-convex lenses, each of 25.4 mm diameter and 50 mm focal length (F no. 2). The focused laser beam travels through 4 mm in air, 5 mm thick fused silica window ($n=1.45$) and then 16.7 mm in water ($n=1.33$) to reach the focal plane. The focal point is located 0.7 mm away from the nozzle orifice which has 1 mm diameter opening. With this optical arrangement the minimum laser focal spot diameter achieved in water is nearly 250 μm. Water enters in the nozzle through a radial inlet. But, the radial water supply leads to a vortex flow of water inside the nozzle and results in unstable water flow from the nozzle orifice. Therefore, an annular wall normal to radial direction is incorporated in the nozzle, as shown in Fig. 2. This restricts the vortex formation and leads toward an axial flow of water inside the nozzle, and thus, improves the water flow pattern beyond the orifice [15]. The current design can provide a maximum water-jet speed of ~50 m/s, limited by the strength of the optical window (made of quartz), used for protecting the optical lens from water. The whole set-up remains submerged in water. The water column height above the work-piece is maintained at ~60 mm. The schematic of the underwater cutting head and a photograph of the cutting process are given in Fig. 2.

The investigation has been carried out in two sets of experiments. The first set was carried out to study the variation in process efficiency with the change in mode of operation in 0.5 and 1 mm thick stainless steel sheets. While the second set was carried out to study the effect of different process variables and operational mode on the cut quality, and also to find out the optimal zone of parameters to get good quality cut in 1 mm thick sheets. All experimental runs were conducted at a constant stand-off distance (SOD) of 0.7 mm keeping the focal point at the top surface of work-piece.

### 2.1. Study of process efficiency

In the first set, the effect of operational mode on process efficiency has been studied in terms of specific energy for material removal; and the maximum possible cutting speed for different set of parameters were experimentally determined. Specific energy, S in pulsed mode of operation can be calculated using Eq. (1)

$$S=\frac{P_{in}}{v_c.w.t}\times\frac{T_{on}}{T_{on}+T_{off}} \tag{1}$$

Here '$P_{in}$' is the supplied laser power, and '$v_c$', '$t$' and '$w$' are the cutting speed, sheet thickness, and average kerf-width respectively. '$T_{on}$' and '$T_{off}$' are the laser on- and off- time respectively. The same equation provides the specific energy for CW mode cutting wherein the off-time, $T_{off}$ is zero.

The specific energy obtained for each set of parameters in pulsed mode cutting was normalized by dividing the same obtained in CW mode. Therefore, a value less than unity would indicate better process efficiency compared to CW mode cutting,