Comparison of dry and wet fibre laser profile cutting of thin 316L stainless steel tubes for medical device applications

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**Abstract**
In medical coronary stent fabrication, high precision profile cutting with minimum post-processing is desirable. Existing methods of profiling thin tubular metallic materials are based mainly on the use of Nd:YAG lasers. In recent studies fibre lasers have been used for stent cutting. However, for profiling thin (<4 mm diameter, < 200 \mu m wall thickness) stainless steel tubes, back wall impingements often occur. This paper presents a comparison of wet and dry pulsed fibre laser profile cutting of 316L stainless steel tubes. When water flow was introduced in the tubes, back wall damage was prevented. Meanwhile, heat affected zone (HAZ), kerf width, surface roughness and dross deposition have also been improved compared with the dry cutting. The scientific study on the effect of internal water flow on laser cutting of thin tubular stainless steel material is reported for the first time.

**Keywords:** Precision Laser cutting Stent Water Dross

**1. Introduction**

One of the growing applications of laser micro-machining for medical application is the manufacturing of coronary stents. A stent is a wire mesh tube which is deployed in a diseased coronary artery to provide a smooth blood circulation as referred to Whittaker and Fillinger (2006). Coronary artery disease (CAD) reduces the blood supply to the heart and causes angina. Stenting is a favourable minimal invasive method to open the occluded coronary artery as surgery can be avoided. Kathuria (2005) describes the typical sizes of stents used in clinical practice: diameter = 2–4 mm; length = 15–20 mm. Materials used for this application includes stainless steel, chromium cobalt, nitinol (nickel–titanium shape memory alloy) and tantalum alloys. Laser technology is a most widely used method in processing stents as compared to electro discharge machining, water jet cutting, braiding, knitting and photochemical etching as reported by Stoeckel et al. (2002). Stent fabrications require a high precision process in order to maintain the slit structures and width. Started with flash-lamp pumped Nd:YAG lasers, laser micro–profiling has been an established tool for coronary stent manufacture. A considerable amount of literatures have been published on Nd:YAG laser applications in stent cutting.

Kathuria (1998) conducted a feasibility study of pulsed Nd:YAG laser precision fabrication of metallic stents. He suggested that a pulsed Nd:YAG laser is a viable tool in creating such fine and mesh structure with slit width of 100 \mu m. High pulse repetition rate with short pulse duration is preferred for the high cut quality. However, the processed samples were not free from dross and spatter adherence. Work by Raval et al. (2004) shows that Nd:YAG laser cutting of stents is associated with slag, oxide layer and unacceptable surface quality.

In the last few years, the emergence of fibre laser technologies has enabled their increasing applications in medical device micro-machining. Kleine and Watkins (2003) conducted a comparative study to evaluate the cutting quality between a pulsed lamp pumped Nd:YAG and a fibre laser. Both systems were adjusted to have nearly the same beam quality and beam diameter. The same processing parameters were applied during cutting processes to accomplish a valid comparison results. They have demonstrated that cutting with an Nd:YAG laser slightly degrades the surface quality due to wider striations zone from the top edge of the laser cut. A study by Liu et al. (2005) identified that flash-lamp pumped Nd:YAG lasers produced large kerf widths and an expansion of heat affected zones due to low facular quality. On the other hand, the poor stability laser outputs of the Nd:YAG laser caused difficulty in reaching small and consistent kerf width in micro-machining. Recent investigation by Meng et al. (2009) demonstrated that cutting quality (heat affected zone and average roughness) was better with a fibre laser compared to an Nd:YAG laser due single mode output and small focused size of the fibre laser. Miller et al. (2009)
explained that embrittlement of metal in the heat affected zone may lead to crack formation and expansion of the stents which may cause crack propagation and device failure. Thus significant costs are associated with post-processing of Nd:YAG laser machined stents to produce high quality products. From the aforementioned studies, fibre laser is seen as a potentially new technology in stent micro-machining which heat affected zone, kerf width and dross could be diminished to a minimum.

The other issue arises in stent micro-machining is the back wall damage either processed with Nd:YAG or fibre lasers. Preventing back wall damage is a challenge in cutting such small and thin tubes. The ejected materials from a cut kerf in a form of hot particles adhere and create back wall damages to the opposite wall of the tube. Back wall damage would cause rough surface finish and cracks to the stent structures due to the dissipation of heat by the ejected particles. On the other hand, the laser beam transmission was also not prevented from reaching the opposite wall causing deterioration to the back wall. Raval et al. (2004) and Kathuria (2005) managed to protect the laser beam energy transmitting to the back wall by inserting the Teflon and Teflon coated brass through the inner wall. A patent by Merdan and Shedlov (2005) discloses a back wall damage prevention method in stent manufacturing. A conduit fluid source through the tube was proposed to wash away the debris and cooling any heat that generated during the cutting. One of the suggested fluids to be used is water. Meng et al. (2009) in their work designed and utilized the tube cooling equipment that could pump water through the tubes during the process in order to reduce the heat affected zone and prevent any damage to the opposite surface of the tube. However, there is no scientific work published regarding the performance of fibre laser cutting with and without water flow.

The present work aims to investigate the basic characteristics of fibre laser cutting of stainless steel 316L tube and understand the effect of introducing water flow in the tubes on minimising back wall damages and thermal effect. The influence of laser parameters upon cutting quality for fixed gas type and gas pressure was investigated.

2. Experimental procedures

2.1. The stent cutting system

The tube profiling system used was a Swisstec Micro T15 machine designed for stent production. This system was integrated with a GSI JK100FL single mode fibre laser with 100 W peak power. The system also includes a CNC motion system (3 axis: rotation, transverse and height), a beam collimator, a cutting head with housing a focusing lens, a coaxial gas nozzle and a CCD vision system looking directly down to the nozzle at the cutting area. A computer control module was integrated for the process parameter selection and control. The fibre laser has a 1080 ± 5 nm output wavelength, 25 μm theoretical spot size at the focal plane and a beam quality factor, M² < 1.1. The coaxial assist gas nozzle had an exit diameter of 0.5 mm. The nozzle was optimized for maximum velocity and coaxial gas flow. This equipment has the ability to pump the water inside the tube as an additional means of cooling during the cutting process. The laser remains stationary and the tube rotates and traverses automatically during laser machining.

2.2. Materials

In this work, 316L stainless steel with an outer diameter of 3.175 mm and 150 μm wall thickness was used. The chemical composition for the material is given in Table 1.

2.3. Cutting experiments

The cutting experiments were performed in two cutting conditions, dry and wet by using the pulsed laser mode. Nitrogen was used as an assist gas. Dry cutting has been performed with the presence of the N₂ assist gas, and the wet cutting was performed with the presence of an assist gas (N₂) and continuous water flow through the inner part of the tube along the tube axis. In the wet cutting, the water pipe with the same diameter of the tube was connected to the tube opening and to the water supply container. In this case, the water flow rate was measured to be 1567 mm³/s which was kept constant during the experiment. Preliminary experiments were carried out to determine the appropriate processing parameters to be used for the comparative study. The range of parameters chosen was based on necessary average power needed to achieve a full depth penetration for both cutting conditions at the selected cutting speed ranges. Laser peak pulse power, frequency, pulse width and the cutting speed were varied in the experiments and their variation ranges are shown in Table 2. The range of cutting speed was selected from 250 mm/min to 2000 mm/min which is the limit of the machine. The parameter variation used was the same for dry and wet cutting condition. The gas pressure was constant at 6 bar for all the cutting experiment performed, limited by the machine. The cutting quality factors investigated were kerf width, surface roughness, dross deposition, back wall damage and heat affected zone (HAZ).

In this study, the Computer Aided Design (CAD) data of the cut profiles was created and transferred to the Micro T15 computer system. The data were translated into G-code programming by the computer system which enables one to perform the cutting process with the desired profiling pattern. In order to study the quality characteristics of the fibre laser stent cutting system, a simple geometry was designed to cut the stainless steel 316L tubes. Initially, the tubes were cut into two separated parts; Part A and Part B as shown in Fig. 1. The simple geometry was used to assess the basic characteristics including kerf width, back wall damages and HAZ. A more complex profile was used to assess the heat effects, particularly along the cut kerf.

3. Results

3.1. Effects of cutting parameters upon kerf width and surface roughness

Fig. 2 shows the relationship between the kerf width and laser cutting parameters. The standard deviations were taken as error
bars. The results show that the kerf width increased as the peak pulse power, frequency and pulse width increased (Fig. 2a–c). During the cutting process, the average power supplied was controlled by these three parameters. The small variation in average power resulted in a large variation of kerf width. Increasing the speed led to reduction of kerf width after a critical cutting speed was achieved (Fig. 2d). Less interaction time between the laser beam and material reduced the energy supplied to the cut kerf, and thus less amount of material was melted. The kerf width variation was investigated by varying the speed between 250 mm/min and 2000 mm/min (maximum equipment speed limit). Critical cutting speed for dry cutting and wet cutting were 1250 mm/min and 1000 mm/min, respectively, where the kerf width started to decrease after these particular points. The kerf widths obtained in this experiment were within the range of 28–40 μm. Minimum kerf was obtained at the highest cutting speed, 2000 mm/min. From Fig. 2, it can be clearly seen that the wet cutting produced a low kerf width compared to dry cut. In addition, it is seen that kerf width increases with the repetition rate in the fibre laser cutting as more energy was delivered to the process.

Fig. 3 shows the influences of laser parameters upon surface roughness. The surface roughness increased with the increasing peak pulse power. However, the surface roughness reduced when the peak pulse power increased from 90 W to 100 W (Fig. 3a). Higher pulse frequency improves surface quality as shown in Fig. 3b. Pulse width significantly affects the surface roughness with a rougher cut surface produced as the pulse width increases (Fig. 3c). From Fig. 3d, surface roughness decreased as the cutting speed increased until 1250 mm/min for the dry cut and 1000 mm/min for wet cut. After these points, the surface roughness gradually increased and were more pronounced at higher cutting speed for wet cutting. This result shows that more power is required after certain point of speed to improve surface quality. In comparison with dry cutting, wet cutting led to better surface quality.

3.2. Dross formation

The dross formation after the laser cutting in dry and wet cutting condition was observed as shown in Fig. 4. From the observation, the processed samples were not free from dross. In both cutting conditions, the dross deposition was heavy at the low cutting speed of 500 mm/min and slightly reduced at 1000 mm/min. The molten material was not totally ejected out from the cut kerf and was attached to the bottom side of the cut wall. Above 1000 mm/min, the dross formation is not significant. By comparing the dross deposition at cutting speed 1000 mm/min for both wet and dry cutting conditions, dross was significantly reduced in the wet cutting condition at 1000 mm/min. In inert gas cutting, the energy solely came from the focused laser beam. The presence of inert gas does not contribute any additional energy to the cutting point (cooling of the cut

![Fig. 2. Kerf width as a function of laser cutting parameters in dry and wet cutting: (a) peak pulse power, (b) frequency, (c) pulse width and (d) cutting speed.](image-url)
zone may be resulted) thus producing high viscosity and high surface tension of molten material. The obtained results showed that 6 bar gas pressure was not enough to act as a mechanical force to drag away the molten material. The presence of water was not sufficient to clean the dross. Water flow, however, helped to achieve a reduction in dross. It is shown that higher-pressure inert gas is required to clean the dross in achieving high cutting quality.

3.3. Back wall damage

Preventing back wall damage is a challenge in cutting small and thin tubes. The ejected materials from a cut kerf in a form of hot particles adhered and created back wall damages to the opposite wall of the tube. Back wall damage would cause rough surface finish and cracks to the stent structures due to the dissipation of heat by the ejected particles. On the other hand, the laser beam transmission was also not prevented and transmitted to the opposite wall causing deterioration to the back wall. In the dry cutting, it can be observed that the undesired particles were scattered on the opposite wall and this phenomenon was not avoidable by changing cutting parameters (Fig. 5a). Heat contained in these particles was transferred to the back wall. In the wet cutting, a clean and spatter-free back wall was obtained as can be seen in Fig. 5b. The continuous water stream carries away the hot particles after they are ejected from the cut kerf and minimizes the heat transfer to the back wall. Fig. 6a and b compares the surface profile analysis of the back wall for both wet and dry cutting conditions. The wet cutting seems to be effective in preventing the back wall damage.

3.4. Heat effects

Heat effect on the surrounding material is a critical factor in cutting thin materials especially in medical device application. Small and thin materials are very sensitive to thermal distortion. Experiment results show that shorter pulse width and low average power reduced the thermal distortion. A shorter pulse width is always rec-

Fig. 3. Surface roughness as a function of laser cutting parameter in dry and wet cutting: (a) peak pulse power, (b) frequency, (c) pulse width and (d) cutting speed.

Fig. 4. Dross deposition at different cutting speed in different cutting condition.
omended in cutting materials sensitive to distortion. At a high average power (40 W), dry cutting (Fig. 7a) resulted in a noticeable thermal effect and surface oxidation along the cut while wet cutting (Fig. 7b) reduced this effect even at high average powers. A more complex profile similar to a medical stent was used to assess the heat effect particularly along the cut kerf. Fig. 8 shows the thermal discoloration in dry stent cutting, while cutting in the water assistance condition gave a clean and bright surface. Wet cutting relatively created a controllable heating during the cutting process and reduced the extent of heat significantly that benefits particularly in cutting thin and small diameter tubular materials.

The heat affected zones (HAZ) corresponding to a high average power (40 W) for both cutting conditions were compared after the laser cut samples were undergone a series of grinding, polish-
4. Discussions

In fibre laser cutting processes, many factors affect the cutting quality. To understand the effect of each processing parameter, the approach of varying one parameter at a time and keeping the other parameters constant was used. In this experiment, the varied parameters were peak pulse power, pulse width, frequency and cutting speed. The average power, $P_{ave}$ can be obtained from:

$$P_{ave} = \frac{P_p \tau f}{FS}$$

where, $P_p$ is the peak power, $\tau$ is pulse width and $f$ is pulse frequency.

Increasing all these three parameters ($P_p$, $\tau$, $f$) will lead to the increase of laser average power delivered to the cutting process. Higher average power generates more energy transfer to the kerf and increases the amount of melted material which translates to a wider kerf. Increasing the pulse width causes a larger kerf due to more material being melted and removed by the gas. As the cutting speed reduces, the interaction time between laser beam and material increases which creates a larger kerf. Increasing the peak pulse power and pulse width resulted in increasing surface roughness. Higher frequency applied to the cutting process improves surface quality due to high pulse overlapping. Kerf width and surface roughness results seem to indicate that pulse width is a dominant factor affecting the cutting quality. The findings from this study suggest that the introduction of water flow inside the tube reduced the local heating during the laser cutting process thus minimized the amount of melted material and produced narrower kerfs. On the other hand, the presence of water improves the melt flow behaviour reduced surface roughness as compared to that in the dry cut.

In this experiment, with the flowing water, a clean back wall and low thermal effect even at high average powers and high pulse energy was demonstrated. Fig. 10 illustrates the mechanism of molten material behaviour after being ejected from cut kerf in dry and wet cutting. The molten metal solidifies and forms undesired spatter on the back wall in the case of dry cutting (Fig. 10a). This created damages to the opposite wall as the wall thickness is thin and thus thermal conduction is not as efficient as in case of thick walls. Fig. 10b shows the clean and spatter-free back wall that was obtained by using the wet cutting. Water flow from the inner diameter of the tube ideally removed all the molten materials before they permanently adhere to the back wall.

Significant improvements with wet cutting to minimize the heat effect and back wall damage were achieved in this work. As every single stent strut needs to be cut without any defects, the water preventive method shows promising results in reducing the heat effect and back wall damages. This is due to the water stream that carries away the hot debris which minimizes the heat transfer and impingement to the back wall.

In order to investigate effect of the water in attenuating the laser transmission during the wet cutting, water transmission spectrum was measured for the 900–1100 nm wavelength at every 1 nm...
by using an Ocean Optics spectrometer (Fig. 11). The measurement was made with a water path length of 1 cm. The relationship between light transmission and absorbance can be obtained based on Beer–Lambert law as referred in Robinson (1996):

\[ A = -\log_{10} T \]

(2)

where \( A \) is absorbance and \( T \) is transmittance. The absorption coefficient, \( \alpha \), is defined by:

\[ \alpha = \frac{1}{x} \ln \left( \frac{1}{T} \right) \]

(3)

Here, \( x \) is the water path length. The absorption length, \( z \) therefore is related to the absorption coefficient, \( \alpha \), and is given by:

\[ z = \frac{1}{\alpha} \]

(4)

From Eqs. (2), (3) and (4), the water absorption spectrum was calculated and plotted based on the transmission data obtained from spectrometer. Through the above calculations, the light absorption length for water media is around 4.2 cm for fibre laser wavelength (\( \lambda = 1080 \pm 5 \) nm) as shown in Fig. 12. The absorption spectrum for this spectrum band is in agreement to the results shown by Kruusing (2004).

The water thickness flowing inside the tube is \( x = 0.2875 \) cm. Based on the Beer–Lambert law, the fraction of the light absorbed by each layer of solution is proportional to the path length. Thus, the transmission for water path length, \( x = 0.2875 \) cm has been computed based on the spectrometry analysis. The transmission obtained for this particular water path length is 94%, which indicates that most of the beam intensity strikes the back wall and showing that water does not absorb much laser intensity. This elucidates that the transmission and absorption of light in water is associated with the light path length in water. High absorptivity of laser energy could not be expected in a thin water path length. However, the transmission is expected to be <94% due to existence of molten material (produced during cutting) in the water that slightly increases the attenuation.

The spectrum analysis shows that water does not play a significant role in attenuating the laser beam in cutting small diameter tube since the 100% absorption can be obtained at around 4.2 cm of water depth. In wet cutting, water played an important role in cooling the work piece and carries away the debris rather than attenuating the beam. A constant rate of water circulation removes local heating of water adjacent to the cutting surrounding and improves the cooling. It is well known that water cools the cutting zones more rapidly rather than particular gases or gas mixtures such as air as referred to Kruusing (2004).

In the current work, the wet cutting results obtained were not free from dross attached to the cutting edge. A conceivable reason was the inadequate inert gas pressure which is not sufficient to force away the molten material from the cutting area in preventing dross.

5. Conclusions

The experimental results comparing dry and wet stainless steel 316L tube cutting were reported. Wet cutting enabled significant improvement in cutting quality. Wet cutting resulted in narrower kerf width, lower surface roughness, less dross, absence of back wall damages and smaller HAZ which would lead to reducing the cost of post-processing. Laser average power and pulse width play a significant role in controlling the cutting quality. Increasing the pulse width increased beam/material interaction time which increased the kerf width and surface roughness. Wet cutting is ideally suitable for cutting thin wall and small diameter tubes specifically in stent production.

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