Journal of Materials Processing Technology 210 (2010) 2261–2267

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

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

N. Muhammad[a,*], D. Whitehead[a], A. Boor[b], L. Li[a]

[a] Laser Processing Research Centre, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, P.O. Box 88 Sackville Street, M60 1QD, United Kingdom
[b] Swiss Tec AG, Bahnhofstrasse 7, FL-9494 Schaan, Principality of Liechtenstein, Switzerland

ARTICLE INFO

Article history:
Received 14 May 2010
Received in revised form 9 August 2010
Accepted 21 August 2010

Keywords:
Precision
Laser cutting
Stent
Water
Dross

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 μm 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.

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 electric 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 μm. 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)

* Corresponding author. Tel.: +44 0 1613062350; fax: +44 0 1612003803.
E-mail addresses: Noorhafiza.Muhammad@postgrad.manchester.ac.uk, pjatt_07@yahoo.com (N. Muhammad), David.Whitehead@manchester.ac.uk (D. Whitehead), alanb@swisstecag.com (A. Boor), lin.li@manchester.ac.uk (L. Li).

0924-0136/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2010.08.015

Table 1
Chemical composition of stainless steel 316L (Kathuria, 2003).

Elements	C	Mn	Cr	Ni	Mo	Si	Cu	N	P	S	Fe
%	0.03% max	2.0% max	17.0–19.0% max	13.0–15.5% max	2.0–3.0% max	0.75% max	0.50% max	0.10% max	0.025%	0.010% max	Balance

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, $M^2 < 1.1$. 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 N_2 assist gas, and the wet cutting was performed with the presence of an assist gas (N_2) 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 mm^3/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, surface roughness, dross deposition, 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

Table 2
Cutting parameter ranges.

Cutting parameters	Lower limit	Upper limit
Peak pulse power (W)	70	100
Frequency (kHz)	1.5	4
Pulse width (ms)	0.1	0.2
Cutting speed (mm/min)	250	2000