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Use of Fiber Lasers for Micro Cutting Applications in the Medical Device Industry

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Abstract

The medical device industry has created a big demand for laser micro machining. Flash-lamp pump solid-state lasers are currently used for this application. Many of these lasers are configured to operate near the diffraction limited beam performance to maintain a very small kerf width. In order to meet yields and up-time requirements reliable laser operation and low maintenance are required. Under production conditions it is a challenge to keep such a laser system performing with the consistency required. The fiber laser concept could provide benefits in order to maintain high up-time and high yields. The single mode fiber laser does not need mirror alignment. Diode pumped fiber lasers also reduce maintenance, as flash-lamp changes are eliminated. The compact air-cooled design also helps to save expensive clean room space on the production floor. Recent improvements in average laser power now make the fiber laser suitable for industrial cutting applications. The focus for this work is therefore laser micro-cutting of stainless steel stent implants and this paper presents the first micro-cutting results in stainless steel. Kerf width and surface quality on the sidewall are of special interest. Also presented are laser operating conditions to minimize Heat Affected Zone (HAZ) in stainless steel.

1. Introduction

Micro machining is a key technology for the medical device manufacturing industry. Lasers are commonly used for welding, drilling and cutting for several different products. Probably the most demanding application for micro-cutting in the medical device industry is the cutting of stents. Stents (Fig. 1) are cylindrical metal scaffoldings that are inserted inside a diseased coronary artery to restore adequate blood flow.

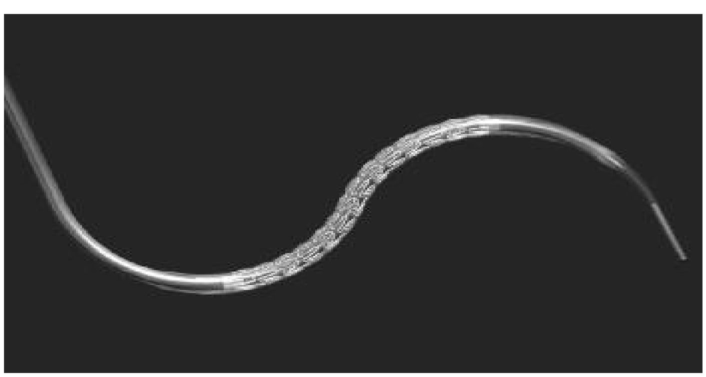

Fig. 1: Stent delivery system

Stents are made out of many different materials, the most commonly used is stainless steel; this paper therefore focuses on the micro-cutting of stainless steel (316L). Other materials used include shape memory metals like NiTi and other super alloys and polymers. The key requirement is a small consistent kerf width and this demands constant beam quality and excellent laser power stability. The laser cut must have a good surface quality with a minimum amount of slag and burr to reduce post-processing, similarly the heat affected zone (HAZ) and molten material recast needs to be small. Fig. 2 shows an SEM picture of a typical stent after cutting and cleaning in an ultrasonic bath.

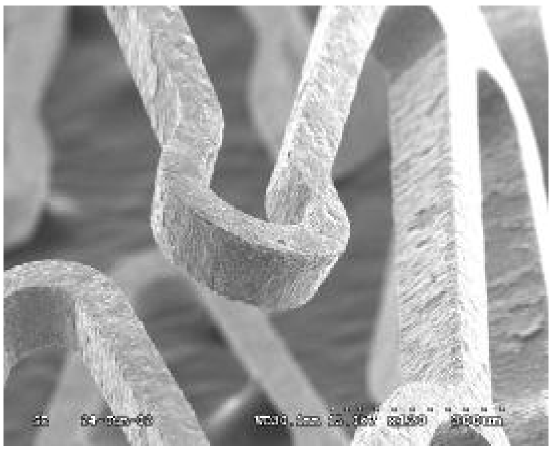

Fig. 2: SEM picture of a stainless steel stent after ultrasonic cleaning

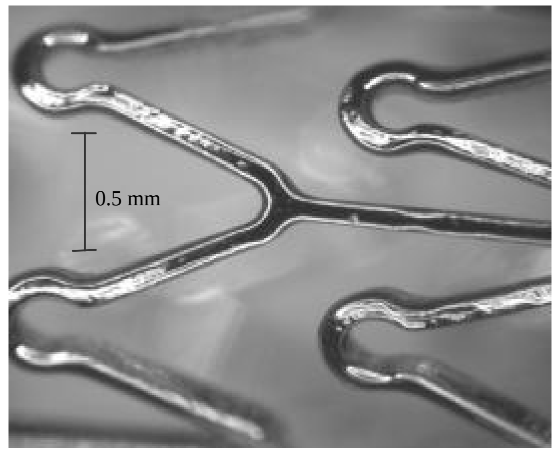

Fig. 3: Stainless steel stent after electro-polishing

After removing some of the slag and burr the stents are electro-polished to achieve a smooth surface finish. Since the stainless steel slag is not conductive it is important to remove it completely from the material surface. Besides smoothing the surface, the electro-polishing process also removes the recast layer to insure the mechanical properties of the implant. Fig. 3 shows a picture of a typical stent after electro-polishing.

2. Background

The flash-lamp pumped Nd:YAG is an established tool for micro-cutting applications. Certain resonator designs achieve the beam quality and pulse power levels required for micro-cutting applications. However, there are several disadvantages of conventional flash-lamp pumped solid-state lasers such as low wall plug efficiency, high running costs and poor thermal stability [1]. Great improvements have been made in order to improve the thermal stability but most conventional lamp pumped laser systems on the production floor still require a high level of maintenance.

Current investigations show that the single-mode fiber laser is an efficient, reliable and compact solution for micro machining. The diode-pumped technology offers low maintenance cycles and high conversion efficiency. Theoretical pump-light conversions of more than 80% are possible [2] but typical optical conversion efficiencies for Ytterbium (Yb) double-clad fiber lasers are 60-70% [3, 4]. Average power levels up to 100 W are possible with air-cooling. Since the overall efficiency is high, most fiber lasers are powered by a standard 110V supply.

This investigation presents cutting results with a 50 W fiber laser (IPG, PYL 50 Series). This investigation was intended to show that the fiber laser is able cut stainless steel material medical implants. In addition, operating conditions to optimize the heat affected zone and surface roughness have been investigated.

3. Experimental Work

3.1. Fiber Laser

The cutting system used for the experiments integrates a CNC motion system, fiber laser, beam collimator and the cutting head (Fig. 4). The cutting head includes a focusing optic and an assist gas nozzle. The nozzle exit hole diameter is 0.5 mm.

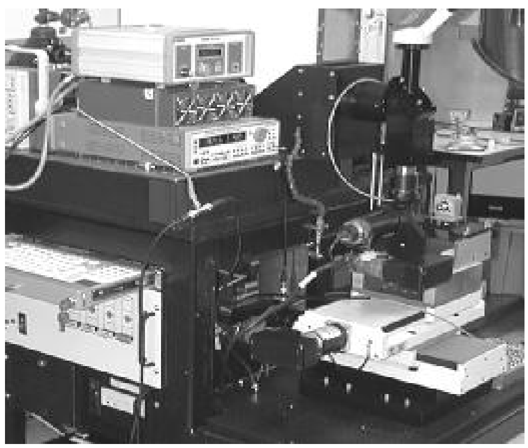

Fig. 4: Experimental cutting system

The fiber laser beam is created in the single mode core of the double clad fiber. The beam quality of the system is $M^2 = 1.1$. In the experiments presented here the laser is collimated to a 5 mm diameter, and then focused with a 50 mm focusing optic. The beam waist (d_f) in the focus can be obtained with [6]:

$$M^2 = d_f \, \phi \, \pi / (2 \lambda)$$

The theoretical calculated focus beam waist is 0.016 mm. The kerf width in the 0.100 mm steel samples was measured and is in the range of 0.018 to 0.020 mm.

3.2. Surface Roughness and Recast Measurements

For the surface roughness measurement a VEECO 3300 N optical profiler with a measurement field size of 0.2 by 0.25 mm was used to determine the surface roughness. The value recorded was Ra (average surface roughness). The sidewall was divided into three sections and the measurements were taken in the center of each section.

The recast layer was measured by cross-sectioning, polishing and etching the sample to make the grain structure visible. The recorded value for the HAZ was averaged from three measurements evenly distributed along the cross section of the sample.

The focus position and assist gas nozzle standoff were kept constant during the experiment. The standoff was 0.5 mm with a focus position optimized to achieve a minimum kerf width. Due to the fact that the fiber laser has no thermal lensing effect, the caustic does not change with variation of the pulse length, pulse power and frequency of the laser pulses. 99.99% pure oxygen was used as the assist gas for the experiments.

4. Results and Discussion

4.1. Effect of Laser Peak Pulse Power on Surface Roughness

In order to investigate the effect of peak pulse power on the surface quality several cuts were made at constant frequency, pulse width, cutting speed and oxygen pressure.

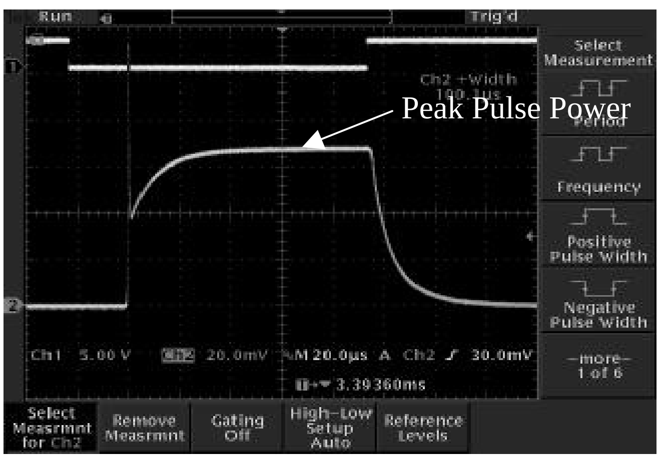

Fig. 5: Typical fiber laser pulse shape

Fig. 5 shows the temporal development of a typical laser pulse used in this work measured with a Tektronix 100 MHz digital oscilloscope and a Thorlabs (DET410/M) InGaAs photo diode.

Gating the pump diodes gates the fiber laser. The laser diode starts to pump the Yb-doped fiber 0.025 ms after the laser trigger signal, the laser output power then stabilizes at a stationary value after an initial spike caused by relaxation oscillation [5]. The initial spike of the relaxation oscillation is < 0.001 ms.. The energy in this spike appears to be insignificant compared with the complete energy in the pulse, therefore in this work; the peak pulse power is defined as the stabilized power during the pulse (Fig. 5).

Fig. 6 shows the relationship between the average surface roughness and the peak pulse power. The cutting parameters for this experiment are 1500 Hz pulse frequency, 0.1 ms pulse length, 6 bar assist gas pressure (O_2) and 4 mm/s cutting speed. The surface roughness measurements are from the top, mid and bottom section of the specimen. Each data point is the average of three to four measurements.

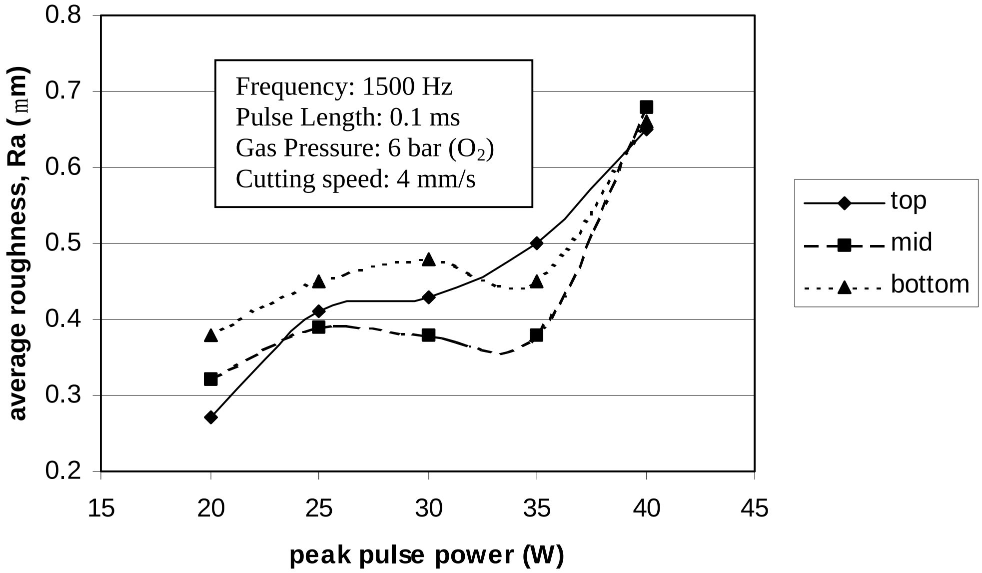

Fig. 6: Average surface roughness as function of peak pulse power

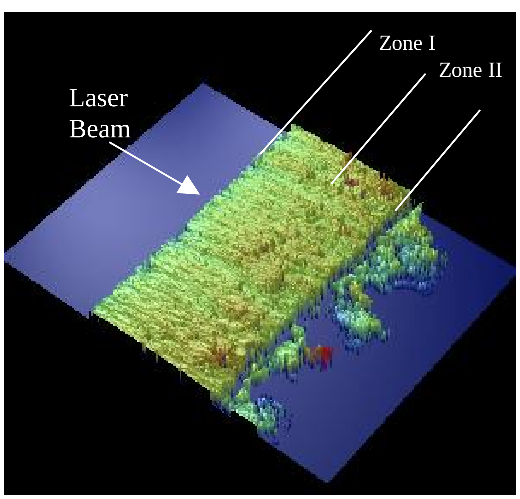

Fig. 7: optical profiler images at 20 W pulse power

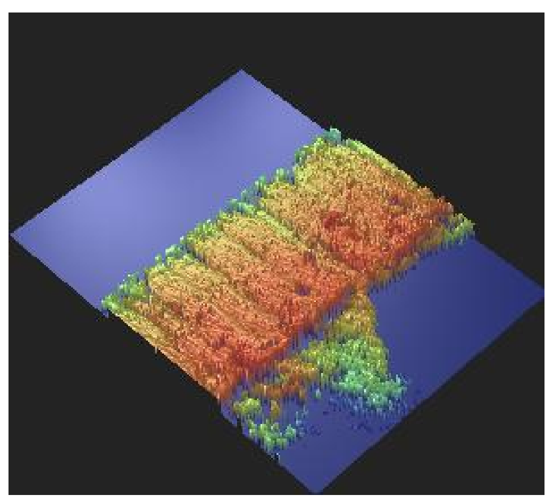

Fig. 8: optical profiler images at 40 W pulse power

The peak pulse power applied to create the cut shown in Fig. 7 was 20 W. It has a typical cut edge that appears to have two distinct zones. Zone I shows regular striations starting from the top edge of the laser cut. In zone II no or indistinct striations can be observed [7]. Fig. 8 shows the edge of a cut that was cut with a pulse power of 40 W. The higher peak pulse power increases the striations in zone I, only at the very bottom does the cut edge have no striations. At lower peak pulse power the surface quality degrades from the bottom to the top edge of the cut edge. In Zone II (also called the melt shear zone) the cut is dominated by the dynamics of the molten metal flow. At lower peak pulse power the surface roughness of the striations in zone I is lower than the surface roughness in zone II. Fig. 6 shows that the surface roughness is increasing with higher peak pulse power due to deeper natural striations along a wider area on the cut edge. The laser pulse frequency is significantly higher than the striation frequency observed in zone I. This effect could be explained by the fact that the individual laser pulses at this frequency do not have sufficient energy to affect the striations and that the natural striation frequency is overriding the pulsing effect of the laser [8].

4.2. Effects of Laser Pulse Frequency on Surface Roughness

Fig. 9 shows the relationship between the average surface roughness and the laser pulse power. Each data point is an average of three to four measurements. The measurements are taken at the top, mid and bottom section of the specimen.

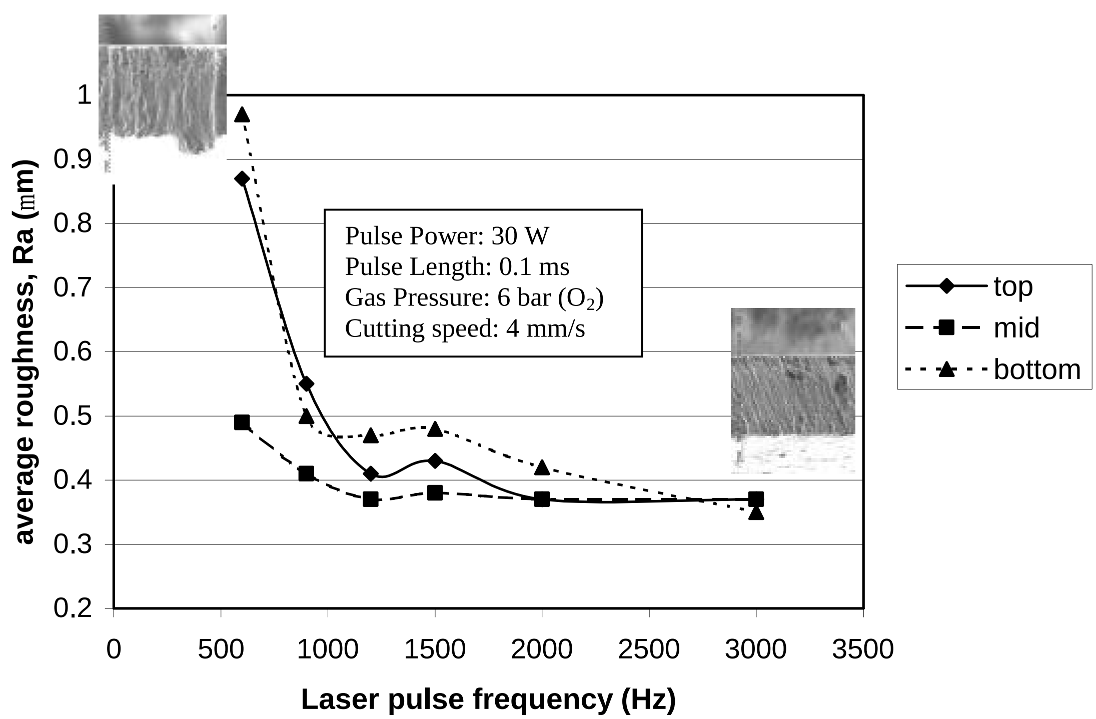

Fig. 9: Average roughness as a function of laser pulse frequency. SEM pictures for 600 Hz and 3000 Hz.

The surface roughness varies from top to bottom of the kerf due to the different material removal mechanisms [9]. (see 4.1). At low pulse frequencies with lower pulse-to-pulse overlap individual laser pulses affect the surface roughness. At higher frequencies the surface roughness improves due to the higher pulse-to-pulse overlap. The surface roughness appears to level off at 85% pulse-to-pulse overlap. Further improvements of the surface quality with higher pulse frequencies are not significant. The effect of the natural frequency of the striations may be overriding the effect of pulsing the laser on the surface roughness at higher laser pulse frequencies (>1000 Hz) [8].

4.3. Effect of laser cutting parameters on recast layer thickness

In order to investigate the influence of laser parameters on the recast layer (Fig. 10) a variation of pulse length, pulse frequency, cutting speed and assist gas pressure was conducted. For this experiment it is important to note that the laser average power was adjusted to the necessary minimum for a complete (successful) cut.

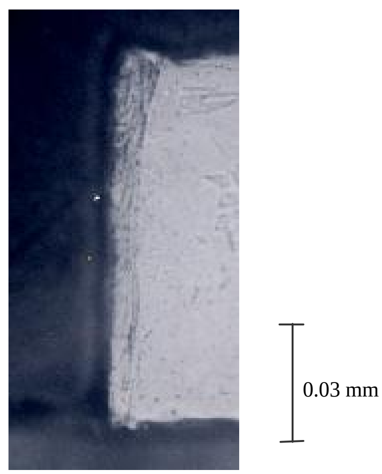

Fig. 10: Cross-section of etched stainless steel sample. The recast layer is visible on the left side of the sample.

An efficient way to determine the significant parameters that influence the recast layer is a DOE (Design Of Experiments). The two-level DOE design with 4 factors is listed in the following table.

Factor	**High level**	**Low level**
Frequency:	2000 Hz	1500 Hz
Pulse length:	0.12 ms	0.60 ms
Assist gas pressure:	7.0 bar	3.5 bar
Cutting Speed:	7 mm/min	4 mm/min

After running the ANOVA analysis (using statistical analysis software) the suggested significant model terms for this experiment are laser pulse length, assist gas pressure and cutting speed.

Model Graphs based on a two level DOE are shown in Fig. 11 and Fig. 12. Fig. 11 shows the influence of pulse length and cutting speed on the recast at the low level assist gas pressure and Fig. 12 does the same at high level assist gas pressure.

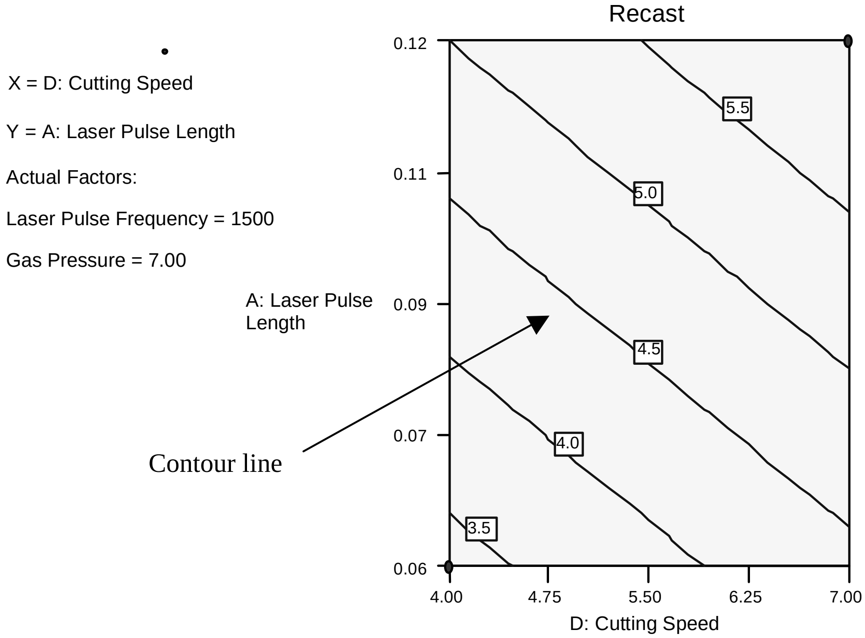

Fig. 11: Influence of laser pulse length and cutting speed on recast layer thickness (in μm) at 7 bar assist gas pressure. The recast layer thickness is labeled on the contour line.

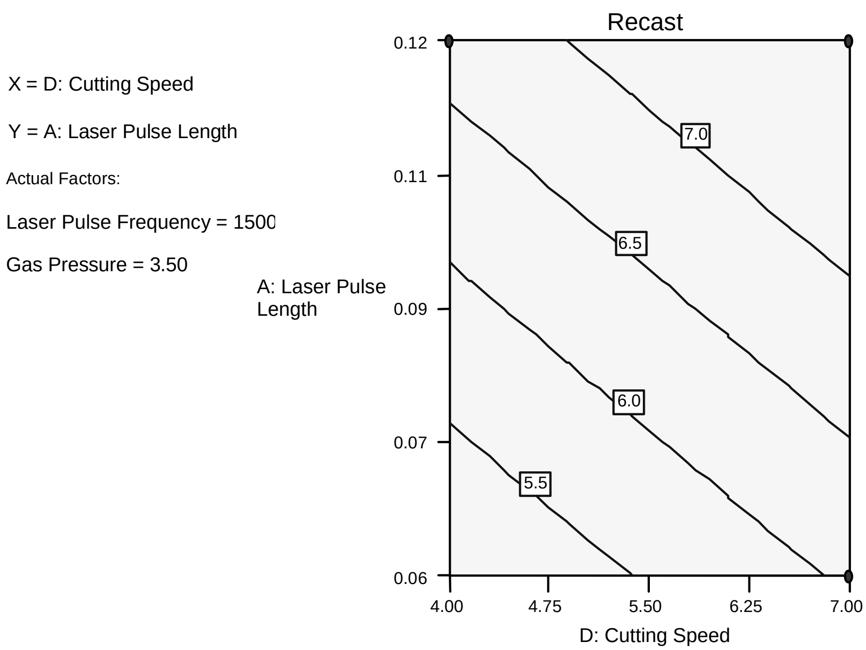

Fig. 12: Influence of laser pulse length and cutting speed on recast layer thickness (in μm) at 3.5 bar assist gas pressure.

Comparing the statistical model graphs of Fig. 11 with Fig. 12 suggests that high assist gas pressure reduces the recast layer thickness. The additional exothermic energy and the increased gas flow at increased oxygen pressure may remove material from the kerf before recast is formed. Fig. 11 and Fig. 12 also suggest that shorter pulses and slower cutting speed are reducing the recast layer thickness. It needs to be noted that the average power necessary to cut at shorter pulse length or slower cutting speed was lower than at longer pulses or faster cutting speed (Fig. 13). This leads to an assumption that the average power level is the major contributing factor to the recast layer thickness.

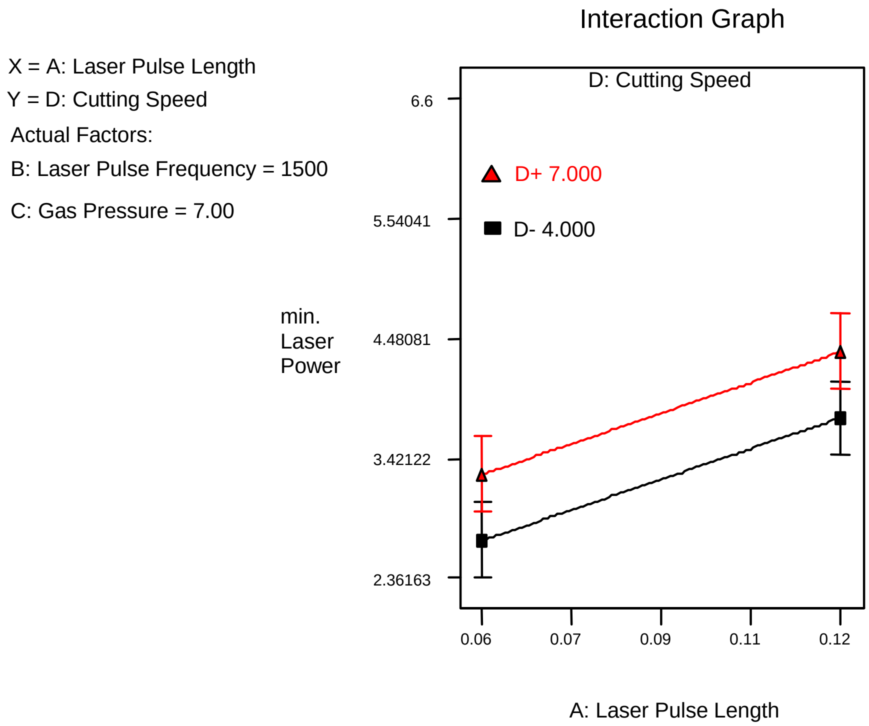

Fig. 13: Influence of laser pulse length and cutting speed on necessary minimum average power.

5. Conclusions

- The fiber laser, due to its good beam quality, is able to achieve very small focus diameters and small kerf widths and is an excellent tool for micro-cutting.
- The cuts produced by the fiber laser show very similar features to those reported with other lasers.
- The surface quality and the thickness of the recast layer of stainless steel can be improved by optimizing the cutting parameters of the fiber laser.
- Lowering peak pulse power results in less pronounced striations and hence improved surface roughness
- Higher pulse-to-pulse overlap improves the cut quality.
- There is no significant improvement of surface roughness beyond 85 % pulse-to-pulse overlap.
- In order to reduce the recast layer, shorter laser pulse length and higher assist gas pressures are desirable.

6. References

1 H.K. Toenshoff, A. Ostendorf, K. Schaefer, Fiber Laser – Compact Source for Micro Welding, ICALEO, 1998

2 V. Reichel, S. Unger, V. Hagemann, H. Muller, M. Auerbach, 8 W highly efficient Yb-doped fiber laser, Proceedings of SPIE Vol. 3889, 2000

3 J. Nilsson, A.B. Grudinin, P.W. Turner, Advanced pulsed and CW high-power fiber laser, CLEO Proceedings, 2000

4 A. Schoenfelder, Fiber lasers address micromachining methods, Laser Focus World, June 1999

5 W. Koechner, Solid-State Laser Engineering, Fourth Edition, Springer, 1996

6 E. Beyer, O. Marten, K. Behler, J.M. Weick, Laser cutting, Laser and Optoelektronik, Sept. 1985

7 C.S. Lee, A. Goel, H. Osada, Parametric studies of pulsed-laser cutting of thin metal plates, Amada Engineering, Jan. 1985

8 V. King, J. Powell, Laser-cut mild steel - factors affecting edge quality, E.I. Monthly, April 1985

9 P.M. Ilavarasan, P.A. Molian, Modeling of Surface Roughness in Laser Cutting, Proceedings of fifth Int. FAIM Conference, Stuttgart, Germany, June 1995