

Pulse Shaping for Micro Cutting Applications of Metals with Fiber Lasers

K. F. Kleine, K. G. Watkins

Laser Group, Department of Engineering, University of Liverpool, Brownlow Street, Liverpool L69
3GH, UK

ABSTRACT

High power single mode fiber lasers are an excellent tool for micro cutting applications. In order to manage the heat input into the material most micro cutting applications require pulsed operation of the laser. Temporal pulse shaping is a proven and enabling technology for many laser welding applications with flash lamp pumped lasers where typical pulse lengths are in the order of 0.1 to 10 ms. The excellent controllability of diode pumped fiber lasers enables pulse shaping during the cutting process with a laser pulse length of typically less than 0.1 ms. For laser micro cutting applications a small kerf width with small HAZ and good surface finish defines the quality of the process. This paper shows the influence of the laser pulse shape on the cutting performance in stainless steel with diode pumped fiber lasers.

Keywords: Fiber laser, micro machining, laser pulse shaping.

1. INTRODUCTION

This investigation presents micro cutting results with a fiber laser in stainless steel (Figure 1). Furthermore it intends to show the influence of pulse shape, pulse length and laser pulse frequency on the cutting performance of the fiber laser system. The heat affected zone (HAZ) in stainless steel consists mostly of material recast due to the high thermal diffusion of the steel. Previous experiments show that the average power level is the major contributing factor for the recast layer thickness [1]. This could lead to an assumption that an efficient cutting process will create a small recast layer. Laser settings that achieve the most efficient cutting process are therefore of high interest.

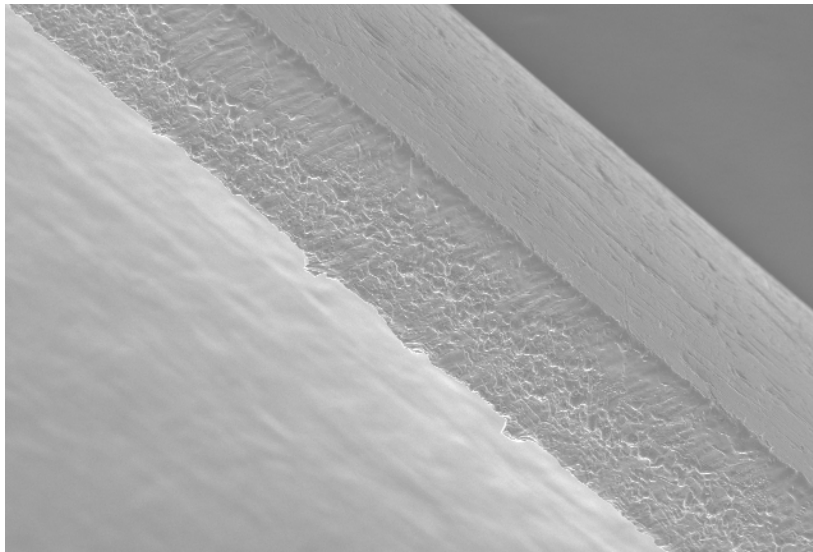


Fig. 1: SEM picture of sidewall cut with the fiber laser

The key requirement for micro machining is a small consistent kerf width, which 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.

2. BACKGROUND

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]. Fiber lasers are pumped with fiber coupled diodes. Those diodes typically have an electrical to optical efficiency of 40%. Therefore, the total wall-plug efficiency of a fiber laser system is in the order of 25-30%. The excellent beam quality and low maintenance make the fiber laser a valuable micro-machining tool for industrial applications.

3. EXPERIMENTAL WORK

3.1. Fiber Laser Micro Cutting System

The fiber laser was integrated into an Aerotech CNC 600 motion controller with UNIDEX 2000 tables. In order to insure optimum position accuracy the maximum feed rate for this micro machining system is 8-10 mm/s. The selected feed rate of 6 mm/s was kept constant for all experiments. The laser beam was focused through a cutting head. The cutting head consisted of a 50 mm achromatic focusing lens and a coaxial assist gas nozzle setup. 99.99% pure oxygen was used as the assist gas for all experiments. The pressure of the assist gas was kept constant at 6 bar. The flow rate through the 0.5 mm nozzle aperture was 0.18 m³/min. The laser system focus position was adjusted once to the smallest kerf width and kept the same during the entire experiment.

Nozzle standoff was optimized and also kept constant for the experiment. The current nozzle configuration will provide the best results if the standoff between the work piece and the nozzle orifice is kept as small as possible. The optimum stand off for this experimental setup was 0.5 mm. A smaller standoff distance could create the risk of nozzle orifice contamination with splatter from molten or vaporized metal ejected from process area. Those contaminations can build up and restrict the assist gas flow.

3.1.1. Fiber Laser System

The fiber laser used for the experiments was a PYL-50M from IPG. The fiber laser system was equipped with a termination module that acts as a collimator. The collimated beam diameter was 5 mm. The maximum continuous wave laser power is 50 W. The wavelength of the fiber laser is 1070 nm with a beam quality factor (M^2) of 1.15. The theoretically calculated beam waist is 0.016 mm. The actual kerf width in the 0.100 mm steel samples was measured and is in the range of 0.018 to 0.020 mm.

Due to the fact that the fiber laser has no thermal lensing effect, the beam propagation does not change with variation of the pulse length, pulse power and frequency of the laser pulses. This will insure that the beam waist is at the same position for all experiments.

3.1.2. Temporal Pulse Control

The temporal pulse control was realized with an arbitrary function generator from Wavetek, Model 175. This function generator provided a block resolution of 8 bit for the power and time domain. This allows shaping the block in 255 steps where each step can be set to one of 255 power levels. One block will then represent one shaped laser pulse. The fiber laser power supply uses a 0-4 V analog input to set the laser diode current from 0-4 A. The diode current controls the

fiber laser's average output power from 0 to 50 W. In order to use the full resolution of the arbitrary function generator for pulse shaping each pulse and to allow for an independent control of the duty cycle the arbitrary function generator needs to be triggered by a separate programmable function generator from HAMEG (HM8130).

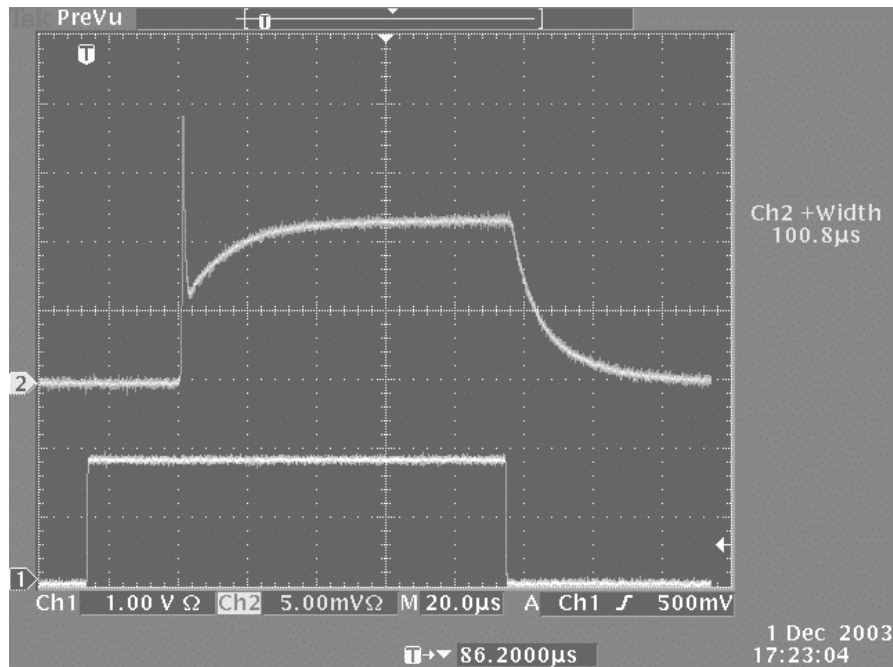


Fig 2: Temporal behavior of a typical fiber laser pulse (top signal) and output signal of the arbitrary function generator (bottom signal) measured with a Tektronix TDS 3012 100 MHz digital oscilloscope and a Thorlabs (DET410/M) InGaAs photo diode.

Figure 2 shows the response of the fiber laser to the signal of the arbitrary function generator. There is a 25 to 30 μ s delay between the input signal and the actual laser power output. This delay can be explained by the response time of the laser power supply to provide the necessary current to the pump diodes plus the time necessary to create sufficient inversion in the gain media of the fiber laser. This delay is dependent on the pulse power level and decreases with increasing power. Those relatively long delays can be explained by the 1/e fluorescence decay time in an Ytterbium (Yb) doped double-clad fiber. The typical decay time for the fiber used during the experiments is 0.8 ms [5]. The onset of the laser pulse shows the typical peak of a pulsed solid-state laser system. The peak is caused by relaxation oscillation in the gain media of the fiber laser. The typical rise time of the fiber laser pulse output is about 0.5 to 1 μ s.

3.2. Minimum Necessary Average Laser Power

The definition for the minimum necessary average laser power is the power level that will enable the laser micro machining system to cut the material at given processing parameters. Previous experiments have suggested that keeping the average laser power as low as possible will result in the smallest thickness of the recast layer. The grade of the stainless steel material is 316 L. The composition of 316 L is Fe, <0.03% C, 16-18.5% Cr, 10-14% Ni, 2-3% Mo, <2% Mn, <1% Si, <0.045% P, <0.03% S.

3.3. Surface Roughness Measurement

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. The value recorded was R_a (average surface roughness). The sidewall was divided into three sections and the measurements were taken in the center of each section. The average of those three values was recorded.

4. RESULTS AND DISCUSSION

4.1. Effect of Laser Pulse Frequency on Minimum Necessary Average Laser Power

In order to investigate the effect of laser pulse frequency on the necessary average laser power several cuts were made at constant pulse width and cutting speed.

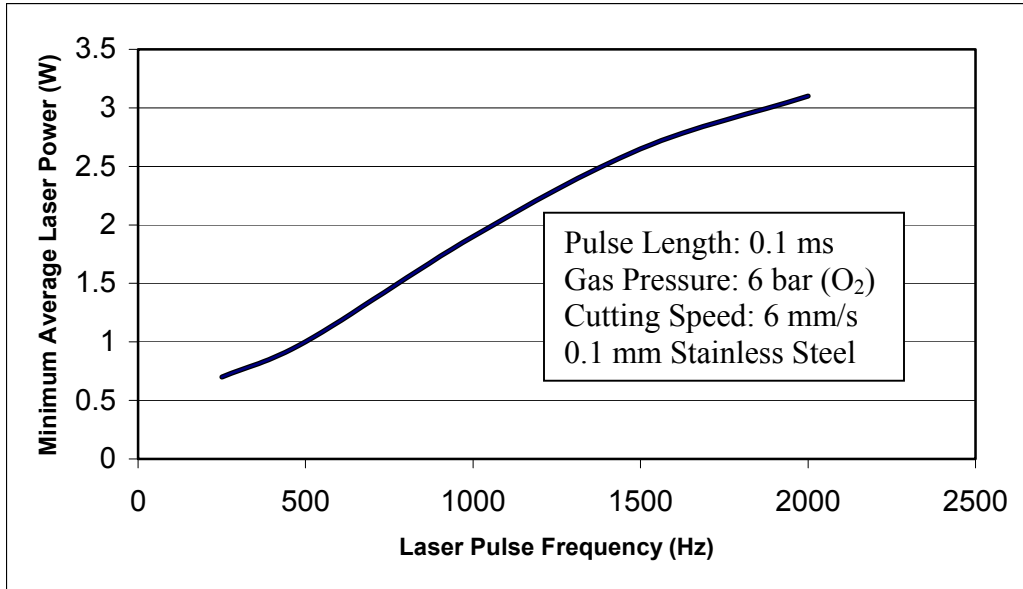


Fig. 3: Average laser power as a function of laser pulse frequency

Figure 3 shows the relationship between minimum average laser power and laser pulse frequency. The lowest average laser power necessary to cut the 0.1 mm thick stainless steel is at the lowest frequency. The lowest tested frequency was 250 Hz. At this frequency the laser pulses almost did not overlap. Any lower frequency will not create a continuous cutting path. Up to a frequency of 1000 Hz each laser pulse had enough energy to cut through the material with one pulse. At higher frequencies the necessary average power increased and seemed to level off at 3.5 W.

4.2. Influence of Laser Pulse Frequency on Surface Roughness

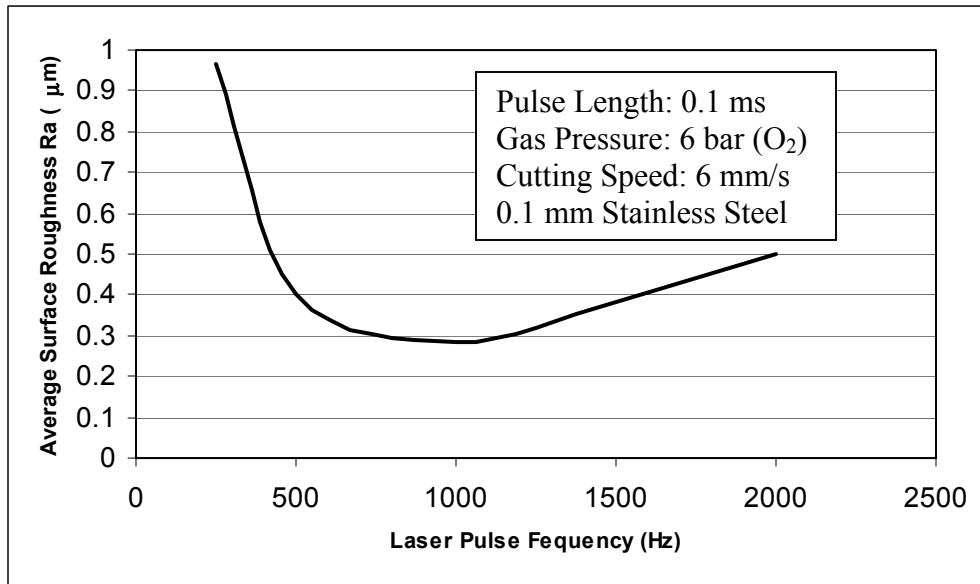


Fig. 4: Average surface roughness as a function of laser pulse frequency

Figure 4 shows the plot of the average surface roughness as a function of laser pulse frequency. For this experiment we only used the minimum average laser power to cut through the 0.1 mm stainless steel at the given process parameter. This plot proposes a minimum surface roughness around 1000 Hz laser pulse frequency. Lower laser pulse frequencies create a steep increase in surface roughness values; higher frequencies are also resulting in an increase, although less steep, in surface roughness. The fact that the surface roughness does not decrease with frequencies higher than 1000 Hz is due to the laser pulse energy. Up to a frequency of 1000 Hz the laser energy in each pulse is high enough so that each pulse cuts through the entire material, and large portion of the material seems to be ejected at the bottom of the interaction zone. At frequencies higher than 1000 Hz the laser process needs two or more pulses to cut through the material. In this process range, more molten material is ejected towards the top of the interaction zone and is melting additional material that creates more slag or recast, resulting in a rougher surface.

Many applications for micro machining require parallel sidewalls. Laser parameters that enable parallel sidewalls with a minimum taper are of interest. Figures 5 and 6 show the influence of laser frequency on the taper of the sidewall. The plots show 1D scans measured with an optical profiler. Both samples were cut with a pulse width of 0.1 mm, 6 mm/s cutting speed and 6 bar oxygen assist gas pressure. The top or laser entrance side is at position $X=100 \mu\text{m}$ the bottom or laser exit side is at position $X=0 \mu\text{m}$.

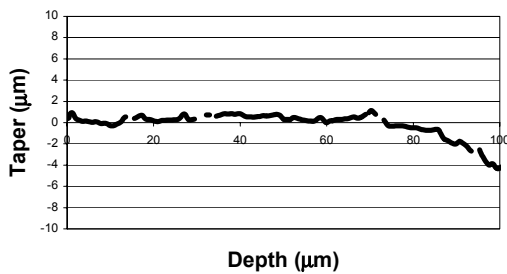


Fig. 5: Optical profiler plot for 1500 Hz laser pulse frequency

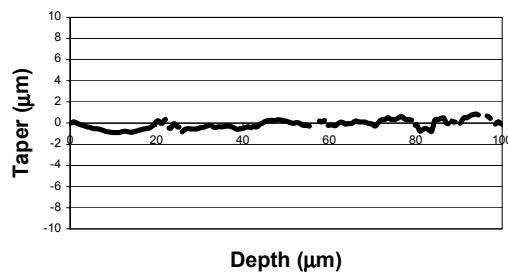


Fig. 6: Optical profiler plot for 500 Hz laser pulse frequency

Figure 5 shows a 4.5 μm taper over a 0.02 mm depth for a laser pulse frequency of 1500 Hz. At 500 Hz, no significant taper is noticeable (Figure 6). Again, the laser pulse energy up to a frequency of 1000 Hz is high enough to cut through the material with one laser pulse. The process of high pulse energy cutting is creating parallel sidewalls with no or small taper. For frequencies of 1000 Hz and higher more than one pulse is necessary in the process area to cut through the material. As already discussed in the previous paragraph, more material is ejected towards the top of the process area and is melting additional material, which results in sidewalls with an increased taper.

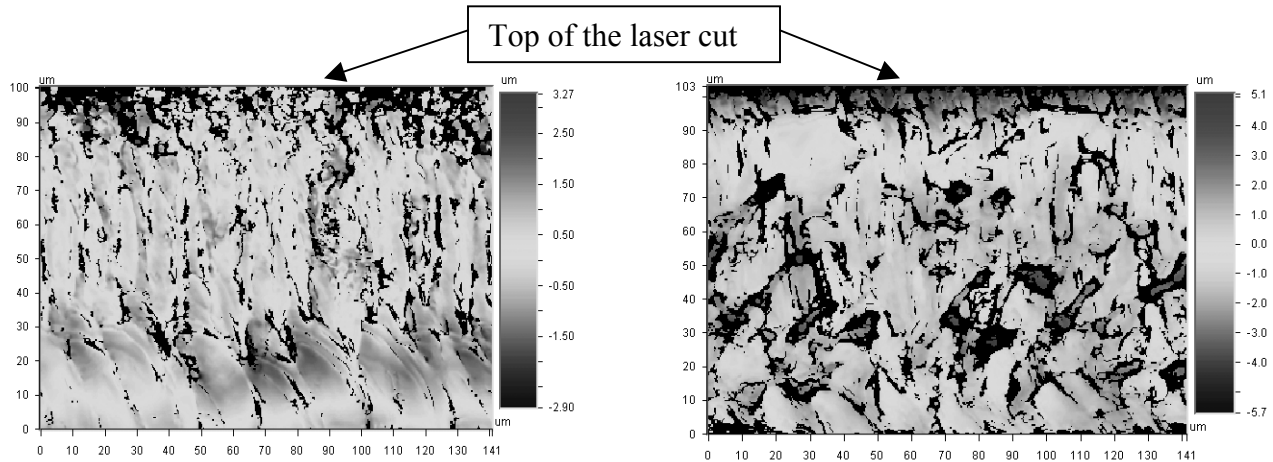


Fig. 7: 2D optical profiler scan for 500 Hz laser pulse frequency

Fig. 8: 2D optical profiler scan for 1500 Hz laser pulse frequency

Figure 7 and figure 8 show 2D optical profiler scans of the laser cut sidewalls of the same 2 samples shown in figures 5 and 6. In addition to the increased taper, structures generated by re-molten material can be seen in the lower part of the cut performed with 1500 Hz.

4.3. Influence of laser pulse shape on cutting quality

For applications where it is not practical to cut through the material with one laser pulse it is necessary to find laser parameters that provide minimum taper, even if the cutting process requires multiple pulses to cut through the material. To achieve this, the influence of the temporal pulse shape on the cutting quality is investigated. Ramped-up and ramped-down laser pulses are compared to the rectangular pulse shape.

Figures 8 and 9 show the signal of the function generator input into the laser power supply and compares them with the laser output of the fiber laser for the ramped-down pulse and ramped-up pulse. Figure 2 previously discussed in section 3.1.2 shows the same for the rectangular pulse.

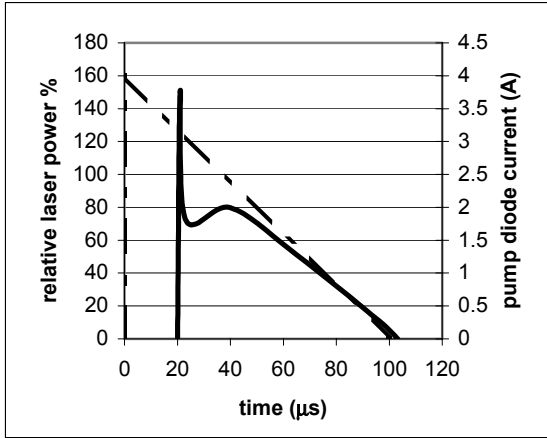


Fig. 9: Response of the fiber laser output (solid line) to a ramped-down diode pumping

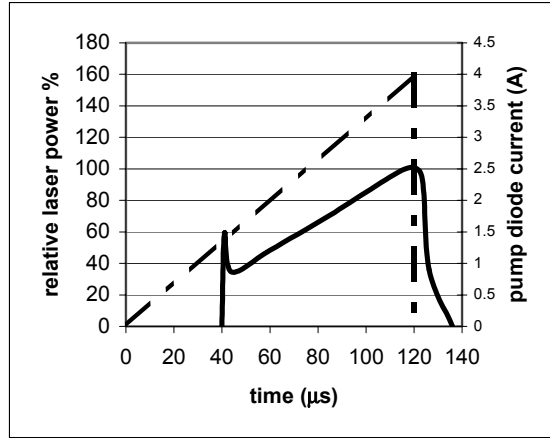


Fig. 10: Response of the fiber laser output to a ramped-up diode pumping

The temporal behavior of the ramped-down pulse in figure 9 shows the same delay and overshoot as a rectangular pulse. Once the laser output power stabilizes it follows the pump diode current. The laser output power for the ramped-up pulse in figure 10 shows a longer delay than the ramped-down pulse. Since the pump power is low at the beginning of the pulse, the time to reach population inversion is increased, leading to an increased delay. The beginning of the laser pulse shows a similar but lower overshoot. Once stabilized the laser output power follows the pump diode current as for the other pulse shapes.

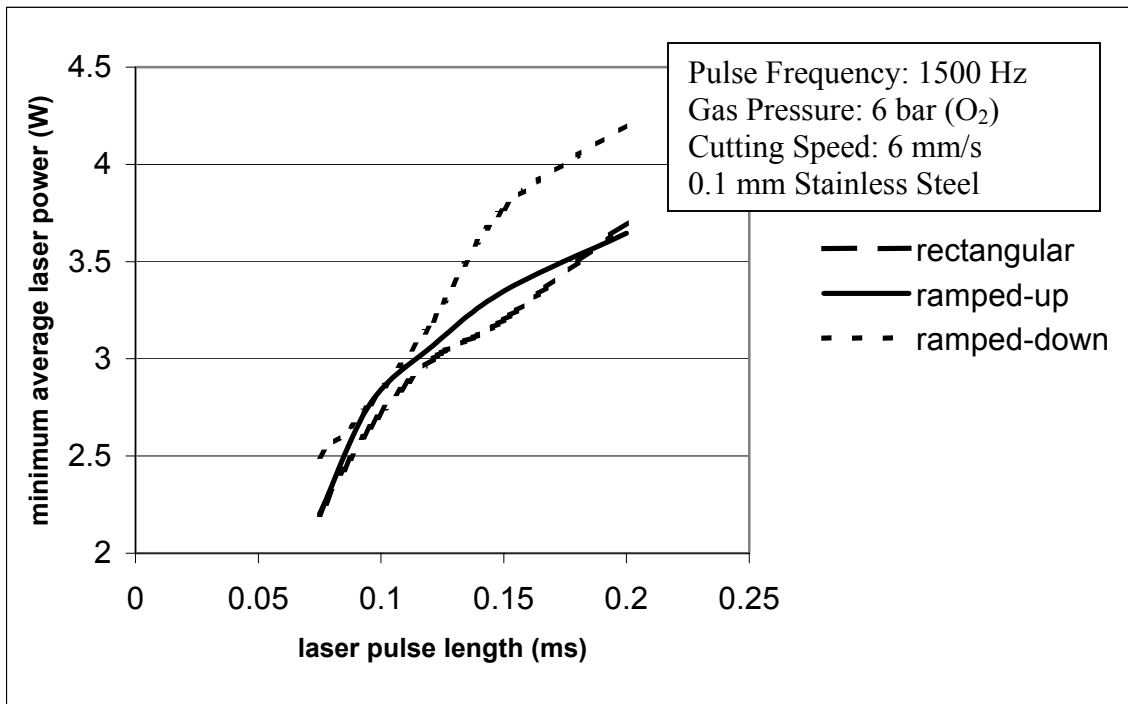


Fig 11. : Minimum average laser power required for cutting as a function of laser pulse length for the three different pulse shapes.

Figure 11 shows the results of cutting experiments with different pulse shapes. The figure plots the minimum average laser power required for cutting against the laser pulse length for the three different pulse shapes.

The ramped-up and rectangular pulses show almost the same laser power requirement. This could result from the fact that the ramped-up pulse does not start at zero laser power (see Fig 10.). The ramped-down pulse requires a higher average laser power than the two other pulse shapes. During the ramp down, the fiber laser power reaches a level where it is below the damage threshold of the material in the process area. At this point the laser power is just heating up the surrounding area next to the process zone and is possibly creating more additional HAZ.

We did not see an improvement in surface finish while evaluating several samples cut with the different pulse shapes. We did see a 25% reduction of the taper for the ramped-up pulse. This agrees with observations from other papers that report a lower taper with a linear increasing sequential pulse delivery pattern [6].

5. CONCLUSIONS

- Controlling the current of the pump diodes for fiber lasers enables the modulation of the laser power for pulsed laser cutting during the laser pulse.
- Shorter pulses require lower average laser power than longer pulses for the laser pulse length range of 0.075 to 0.200 ms.
- The experiments showed that when cutting with lowest possible laser power for given laser parameter set the surface roughness (R_a) has a minimum for a specific laser pulse frequency or laser pulse overlap.
- Low frequencies in combination with small overlap and high laser pulse power could result in reduced taper of the sidewalls but will have increased surface roughness compared to high pulse frequencies with high overlap.
- Ramping up the laser pulse power during the laser cutting process may reduce the taper of the sidewalls.

REFERENCES

- 1 K.F. Kleine, K.G. Watkins, B. Whitney, *Use of Fiber Laser for Cutting Applications in the Medical Device Industry*, ICALEO, Scottsdale, October 2002.
- 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. Grudin, 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 *Ytterbium doped fiber amplifiers*, IEEE JQE 33, p 1049, 1997.
- 6 D. K. Y. Low, et al., *Taper Control During Laser Percussion Drilling of NIMONIC Alloy Using Sequential Pulse Delivery Pattern Control (SPDPC)*, ICALEO, 1999.