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Lumped Parameter experiments for Single Mode Fiber Laser Cutting of Thin Stainless Steel Plate

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Abstract. The present work reports the parameters on laser cutting stainless steel including workpiece thickness, cutting speed, defocus length and assisting gas pressure. The cutting kerf width, dross attachment and cut edge squareness deviation are examined to provide information on cutting quality. The results show that with the increasing thickness, the cutting speed decrease rate is about 27%. The optimal ranges of cutting speed, defocus length and gas pressure are obtained with maximum quality. The first section in your paper

1. Introduction

Stainless steel is being increasingly used in automotive and aerospace structures for its good corrosion resistance and high strength. Due to the advantages of the high brightness, high directivity, laser has been applied to various fields of social productions since it was born in 1960s especially in laser material processing such as laser drilling[1], laser welding[2] and laser cutting[3~10].Laser cutting is an important partition method in such applications. There are several kinds of industrial lasers available at present, including the conventional CO_2 and Nd:YAG lasers as well as recently available high power fiber lasers. In recent decades, fiber lasers are playing an increasing role in laser processing for high photoelectric conversion efficiency, better beam absorption, good beam quality, good cutting reliability, strong flexible light effect and low cost compared to traditional CO_2 laser and YAG laser cutting. For example, Paul A. Hilton et al. presented a diffractive optical element design for thick C-Mn steel plate cutting by fiber laser and concluded that using the DOE and lens combination can reduce the power density in the residual defocused laser beam compared to that from the 500mm lens alone[11]. S. O. Al-Mashikhi et al. studied the effect of cutting speed and sheet thickness on surface oxidation and heat affected zones for laser-oxygen cutting of mild steel with a fiber laser and found that the HAZ is wider at the bottom of the cut than that at the top and there is no simple direct relationship between HAZ width and surface oxidation[12]. Catherine Wandera et al. experimentally investigated high power fiber laser cutting thick-section stainless steel and aluminum with inert gas assisted and obtained the parameter window[13].

In the present study, an investigation into the process characteristics and mechanisms involved in single mode CW fiber laser cutting of 316L stainless steel is carried out with the consideration of cutting speed, defocus length and assist gas pressure. Further, the performance characteristics kerf width, dross attachment and cut edge squareness deviation are optimized for the evaluation of cut quality. The aim of this work is to perform a detailed analysis on the characteristics of single mode fiber laser cutting.

2. Experimental set up

In this study, a single mode CW fiber laser was used with maximum power of P=2000W at wavelength λ=1080nm. As illustrated in Fig.1 there is schematic of the setup used in experiments. The cutting head is controlled by the ABB robot arm using the assembly language to realize the controlling of laser output power, cutting speed, cutting distance and the cutting direction et.al. The lens including collimating lens and focus lens and protection lens are assembled in the cutting head. The protection lens is located below the focus lens to avoid the metal spattering. The focal length is 124mm and the focus is located at the nozzle outlet. Oxygen with a purity of 99.9% is used as a cutting assist gas and it can be adjusted up to 50bar with the cutting nozzle of 1.5mm diameter. The experimental material is 316L stainless steel plate of 1.5mm, 2.0mm, 3.0mm in thickness. The thermodynamic parameters of the metal plate are showed in Table 1. In the experiments, the metal plates are fixed into aluminum frame while the moving program is realized by cutting head.

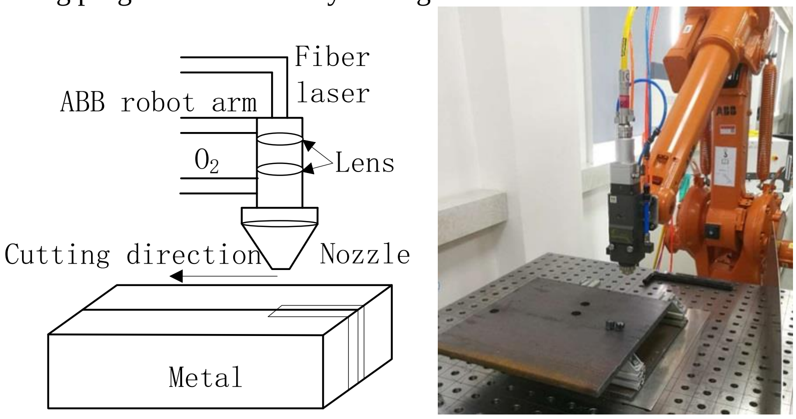


Fig.1. Experimental setup for fiber laser cutting

During the laser cutting process, the nozzle keeps a constant distance about 1.0mm to the sample surface. Assist gas pressure are varied from 0.4 to 2.2 bar in the experiments. Two replications for each experimental run have been performed to make sure the results to be repeatable and valid. After the cutting, the cut quality is initially evaluated by visual observation and microscopic observation and measurement subsequently using optical microscopy. Kerf width and dross attachment and cut edge squareness deviation are measured from these images taken from the cuts. The top and bottom kerf widths are measured using the optical measuring microscope (AFTVISION) at 4* magnifications. To make this more clear schematics illustration of the top view and bottom view and the cross sectional view of laser cut surface are shown in Fig. 2. Here, *d1* is the input kerf width from the top view, *d2* is the output kerf width from the bottom view, *h* is the thickness of the workpiece and *θ* is the cut edge squareness deviation which can be described as[14]:

$$\theta = \frac{(d1-d2)*180}{2*\pi*h} \quad (1)$$

Table1. Thermodynamic parameters of stainless steel

Density (kg/m^3)	7870
Thermal conductivity (W/m/K)	15.1
Specific heat (J/kg/K)	502
Absorptivity	0.307
Melting point (K)	1370
Tensile strength (MPa)	480

According to the dross adhering slag at the lower cutting surface in the cutting morphology, the dross attachment is divided into five level and each level corresponds to a numeric value: 1 equals to dross free, 2 equals to little dross, 3 equals to medium dross, 4 equals to heavy dross and 5 equals to not cut through.

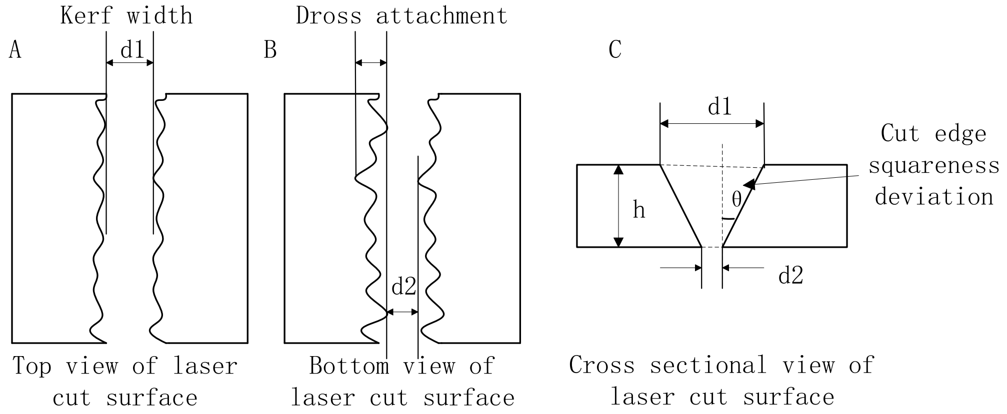


Fig.2 Schematic view of kerf width, dross attachment and cut edge squareness deviation

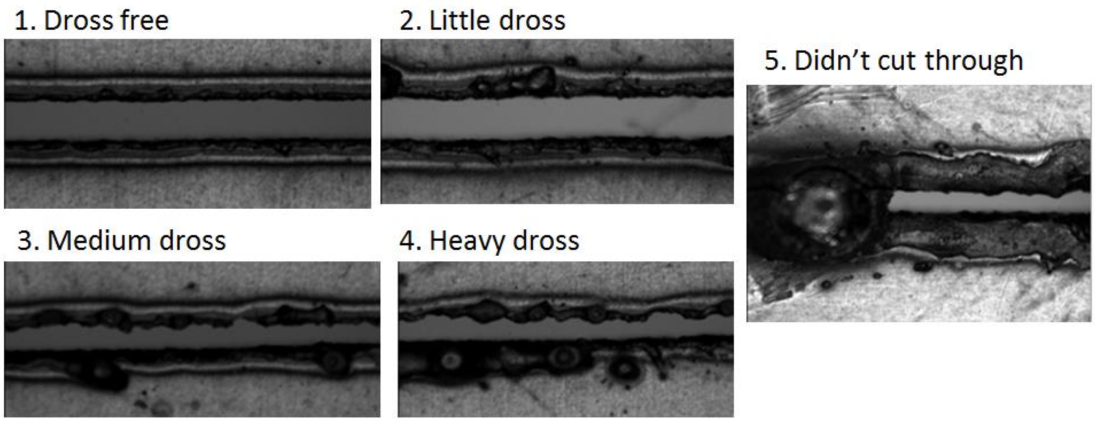


Fig.3 Cutting results for dross attachment level

3. Results and discussion

There are many factors that may affect the cutting quality, for example cutting speed, defocus length, assist gas pressure, laser output power, nozzle diameter et.al. Experiments taken in this paper include three parameters of cutting speed, defocus length and assist gas pressure. In order to secure comparable results, only one parameter is varied in each cut, the other parameters being kept constant.

3.1 Effects of the cutting speed

The effects of cutting speed on cut performance (kerf width, dross attachment, cut edge squareness deviation) are shown in Fig.4. In these experiments, the output power is 2000W, the assist gas pressure is 0.7bar, the defocus length is 5.5mm.

Fig.4A shows the kerf width with the effects of cutting speed for the given three workpiece thicknesses. The primary trend can be obtained that the kerf width is decreasing with the increasing cutting speed and workpiece thickness. Fig.4B describes the kerf width relative to the thickness (w/h) which shows a more clear view of the difference between kerf width and workpiece thickness. The lower cutting speed may increase the interaction time between laser and workpiece which can consequently increase the molten metal removal induced by laser melting and splashing resulting in the wider kerf. Due to the oxidation properties of stainless steel, during the O_2 assisted laser cutting process, lower cutting speed will increase the heat accumulation induced by workpiece oxidation reaction consequently increase the kerf width and cause heavy dross attachment at the bottom kerf as shown in Fig.4C. On the contrary, when the cutting speed is too high, due to less time for the interaction between laser and workpiece, the heat accumulation can't afford to melting or splashing the workpiece which will result in a heavy dross at the bottom kerf and may also cause the un-cut through cases as shown in Fig.5. Therefore, the reasonable control of the cutting speed is one of the keys to achieve high quality and high precision laser cutting.

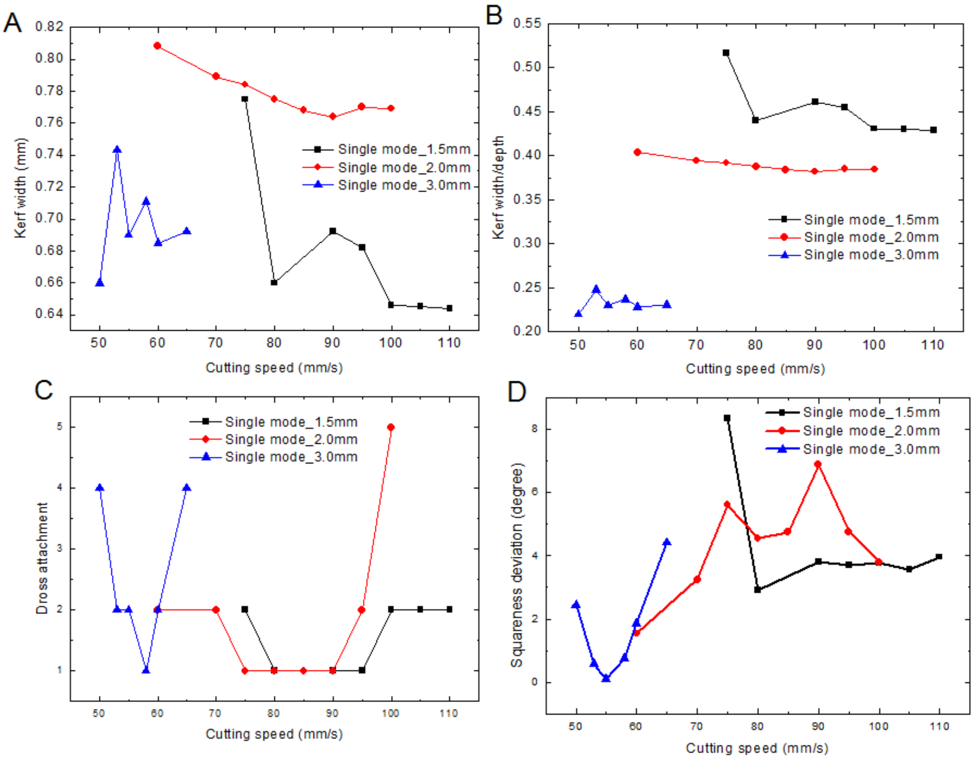
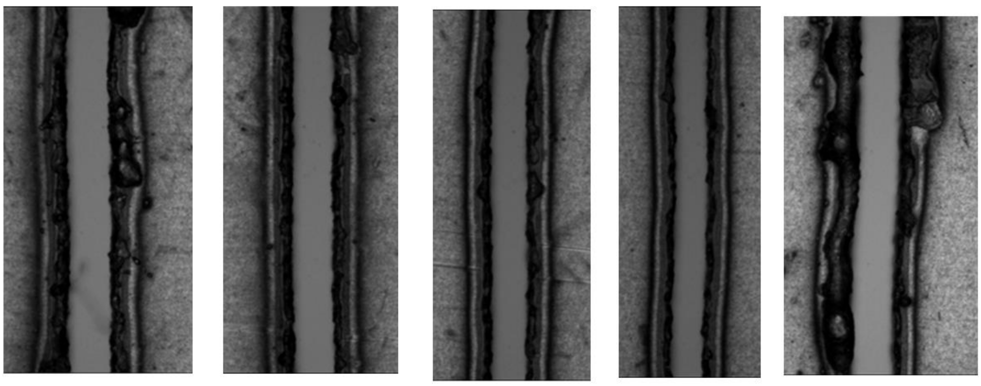


Fig.4 Variation of (A)kerf width(B)kerf width/depth(C)dross attachment(D)cut edge squareness deviation with cutting speed



(a) u=60mm/s (b) u=70mm/s (c) u=80mm/s (d) u=90mm/s (e) u=100mm/s

Fig.5 Bottom view of 2.0mm stainless steel cutting results with different cutting speeds (a~e)

Taken together, the optimal ranges of cutting speed with small kerf width, no dross slag and small cut edge squareness deviation are as follows: 1.5mm for 90~100mm/s, 2.0mm for 80~90mm/s and 3.0mm for 55~60mm/s. The results show that with the increasing thickness, the cutting speed decrease rate is about 27%.

3.2 Effects of the defocus length

During the cutting performance, the defocus length plays an important role for the cutting quality. The defocus length is related to workpiece thickness and the assisted gas species. In these experiments, the output power is 2000W and the assist gas pressure is 0.7bar for 2.0mm and 3.0mm plate and 1.0bar for 1.5mm plate. The cutting speed is varied with the workpiece thickness as discussed in 3.1 section. The cutting speeds are 1.5mm at 85mm/s, 2.0mm at 60mm/s and 3.0mm at 58mm/s. The results are shown in Fig.6. It can be found that the kerf width is increasing with the increased defocus length and the workpiece thickness as shown in Fig.6A. However, the kerf width relative to the thickness (w/h) indicates that the width-depth ratio is decreasing with the increased defocus length and thickness as shown in Fig.6B.

For a certain focusing lens used in this equipment, the increasing defocusing length will change the laser beam spot size and then reduce the energy distribution at the workpiece surface thus resulting in a wider kerf width or even uncut-through. On the contrary, the decreasing defocusing length will increase the laser beam spot size and increase the energy distribution which will result in a narrower cut kerf width and deeper cut depth. For another aspect, small laser beam spot will decrease the oxidation heat and affects the cut quality. The exothermic competition of oxidation and laser heating determines the cutting quality including kerf width, cut depth, dross attachment and the cut edge squareness deviation. The results show that the optimal ranges of defocus length are as follows: 1.5mm for 5.5~7.0mm, 2.0mm for 6.5~7.5mm and 3.0mm for 5.5~7.0mm.

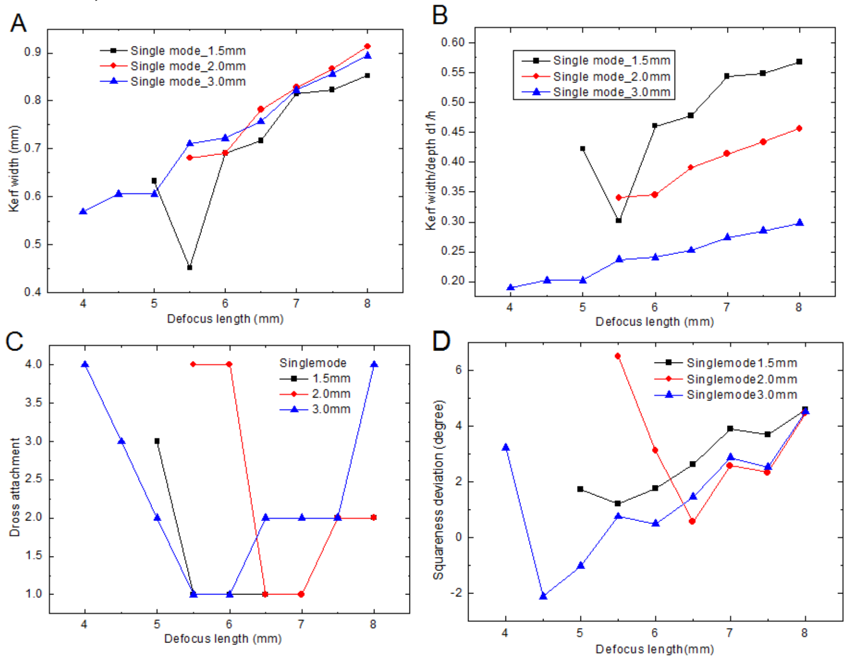
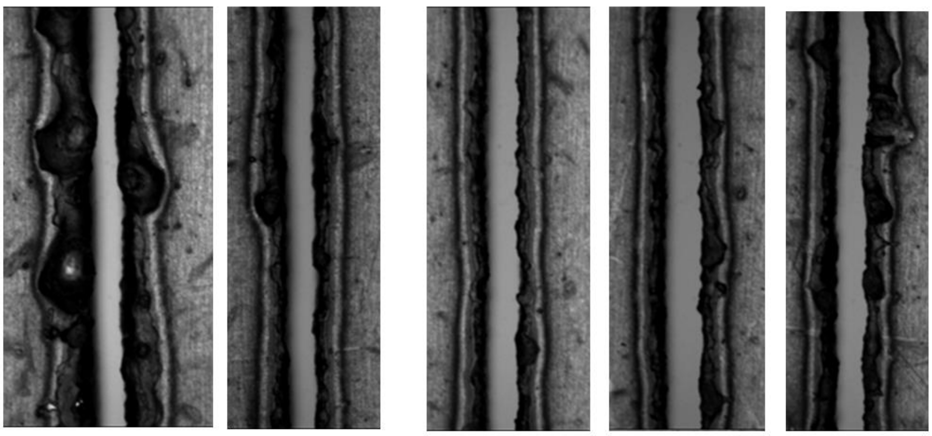


Fig.6 Variation of (A)kerf width(B)kerf width/depth(C)dross attachment(D)cut edge squareness deviation with defocus length



(a) f=4mm (b) f=5mm (c) f=6mm (d) f=7mm (e) f=8mm

Fig.7 Bottom view of 3.0mm stainless steel cutting results with different defocus length (a~e)

3.3 Effects of the assist gas pressure

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The assist gas pressure is varied from 0.4bar to 2.2bar for the three thickness workpieces by single mode laser cutting as shown in Fig.8. From Fig. 8A and B it can be found that gas pressure has less influence on kerf width or the ratio of kerf width and workpiece thickness compared to cutting speed and defocusing length. Fig. 8C shows the variation of dross attachment with gas pressure. Dross free cuts are seldom found with low pressure cutting (p<0.7bar) in this study, which may be due to the low drag force on the cut front under low pressure. It can also be found that dross free cuts are not occurred with high assist gas pressure (p>1.6bar) and it also differs with workpiece thickness. The maximum pressure is decreasing with the thickness for 1.5mm of 1.9bar, 2.0mm of 1.6bar and 3.0mm of 1.3bar, respectively. The dross attachment is worse when the pressure is higher over 1.6bar or below 0.4bar. When the pressure is high, the gas flow will form vortex at the workpiece surface which may decrease the drag force to remove the melted material and resulting in a rough cut surface, wider kerf width and heavier dross attachment. The results are shown in Fig.9.

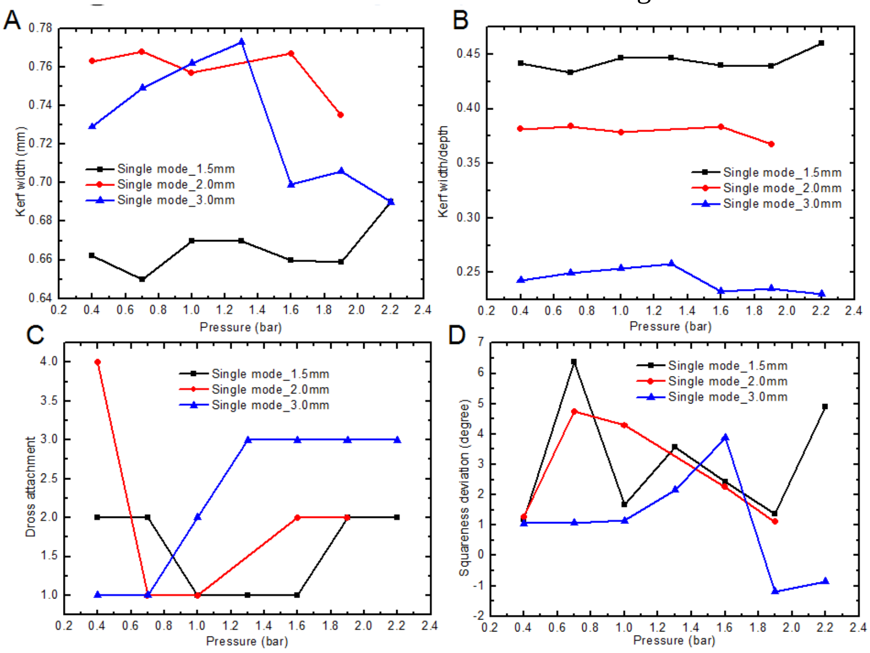
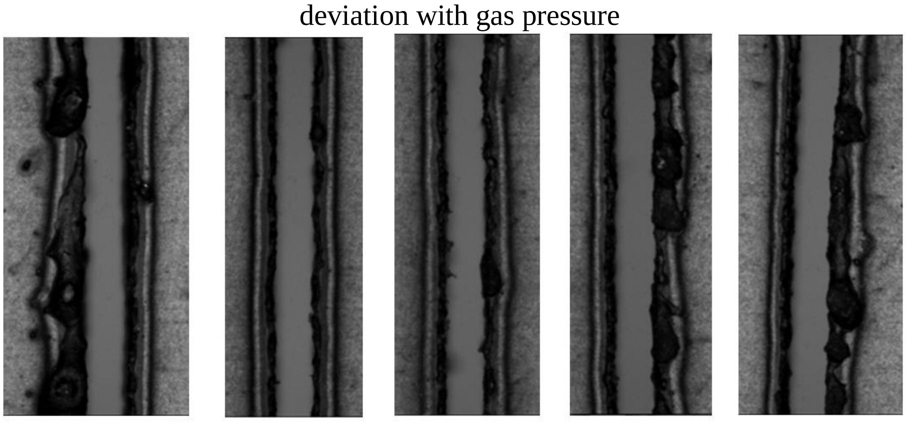


Fig.8 Variation of (A)kerf width(B)kerf width/depth(C)dross attachment(D)cut edge squareness deviation with gas pressure



(a) 0.4bar (b) 0.7bar (c) 1.0bar (d) 1.6bar (e) 1.9bar

Fig.9 Bottom view of 2.0mm stainless steel cutting results with different assist gas pressure (a~e)

On the other hand, since oxygen is used as the assisted gas, the oxidation heats make great contributions to laser cutting progresses. When the pressure is low, the oxidation heats make lower contributions to the material melting and vaporizing which may to some extent decrease the cut depth. Reasonably, the higher pressure can obtain more oxidation heat. However, with the gas pressure increasing, oxidation heat will reach a saturated value which means that the pressure above the saturated value will not be used to supply the oxidation progress. Therefore, suitable gas pressure has an important influence on the cut quality. When the other parameters are kept constant, the optimum pressure is obtained about 1.5mm for 0.7~1.3bar, 2.0mm for 0.7~1.0bar and 3.0mm for 0.4~0.7bar.

4. Conclusion

In present study, four parameters including cutting speed, defocus length, assisted gas pressure and workpiece thickness have been taken into consideration in single CW fiber laser cutting of stainless steel workpieces. Kerf width, dross attachment and cut edge squareness deviation have been estimated as the references of cut quality. The results indicate that faster cutting speed will lead to less time for melting and result in uncut-through while slower cutting speed will cause heavier dross slag for oxidation heat supplied by assist gas. The optimal cutting speed ranges are 1.5mm for 90~100mm/s, 2.0mm for 80~90mm/s and 3.0mm for 55~60mm/s. The higher defocus length will cause larger laser beam spot size and result in larger kerf width while lower ones will cause smaller spot and higher energy focus which lead to more dross slag by the assist gas support. The optimal defocus length ranges are 1.5mm for 5.5~7.0mm, 2.0mm for 6.5~7.5mm and 3.0mm for 5.5~7.0mm. The assist gas pressure has a saturated value to keep a high cutting quality and the optimal ranges are wider with the decreasing workpiece thickness which are shown as follows: 1.5mm for 0.7~1.3bar, 2.0mm for 0.7~1.0bar and 3.0mm for 0.4~0.7bar.

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