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Theoretical and experimental aspects of laser cutting using direct diode laser source based on multi-wavelength multiplexing

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HIGHLIGHTS

- A diode laser with an output power of 2 kW based on the multi-wavelength multiplexing is introduced.
- A theoretical laser cutting model is built to predict the cutting performance of a direct diode laser source.
- The cutting result of the diode laser is better than that of the fiber laser when the thickness of sheet is more than 3 mm.

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ABSTRACT

In this paper, a theoretical laser cutting model based on absorption calculations and the characteristics of multi-wavelength laser beam is introduced to predict the cutting performance of a direct diode laser source (2 kW output power from an optical fiber with a 105 μm core diameter and a numerical aperture of 0.2). Cutting experiments are performed on stainless steel sheets (304) with thicknesses ranging from 1 mm to 10 mm. When comparing with the relevant industrial cutting results using fiber lasers, this diode laser source can obtain a greater speed at the thickness of samples above 3 mm. The experimental results have a good agreement with the theoretically predicted results and demonstrate the cutting ability of the diode laser source of such power class and brightness class for use in industrial laser cutting applications.

1. Introduction

Because of their distinct advantages which include high electro-optical efficiency, compactness, wavelength versatility and high reliability, direct diode laser sources are playing major important roles in material processing of engineering and manufacturing [1–4]. However, current diode laser sources remain unsuitable for numerous applications, e.g., for laser cutting, because of their current-limited beam quality. Laser cutting of metal sheets generally requires high power intensity and high focusability [5]. Consequently, fiber lasers with a wavelength of 1.06 μm and a near diffraction limited beam quality have been dominant in the field of thin metal sheet cutting for a long time. Recently, advances in beam multiplexing technology have made it possible to scale up the power and the brightness of diode laser sources while maintaining acceptable beam quality. Intensive research in this field has been conducted by several companies and research groups (see Table 1). One well-known architecture of wavelength beam multiplexing for kW range diode laser sources was invented by the Massachusetts Institute of Technology (MIT) and commercialized by TeraDiode. For example, a fiber-coupled diode laser source with a power of 2030 W from an optical fiber with a 50 μm core diameter and a numerical aperture (NA) of 0.15 was developed and employed successfully in laser cutting applications [6].

To date, much of the research has focused on development procedures of these diode laser sources and demonstrations of their cutting abilities. Unfortunately, the theory of the interactions between multi-wavelength multiplexing diode laser source and the metal materials, as well as cutting theoretical models of these diode laser sources have rarely been investigated. Thus, this is a limitation for future research of diode laser cutting applications. In this work, to introduce the theory of diode laser cutting, we employ a diode laser source which is developed by ourselves. The development of this diode laser source is based on building block platform. By combining dense spectral multiplexing, polarization multiplexing and coarse spectral multiplexing, the resulting diode laser source can produce a power of 2045 W from an output fiber with a 105 μm core diameter and a NA of 0.2. According to

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Table 1
Commercial diode laser sources used in laser cutting. Data are given without any claim to completeness.

Institution	Multiplexing element	Power	Fiber parameters	Successful cutting tests published
Teradiode [6]	Surface grating	2030 W	50 µm 0.15 NA	Y
Limo [7]	Dielectric filters	2000 W	200 µm 0.2 NA	Y
Direct Photonics [8]	Thin film filters	500 W	100 µm 0.15 NA	Y
DILAS [9]	Ultra-steep dielectric filters	800 W	100 µm 0.17 NA	Y

the absorption calculations and the characteristics of the multi-wavelength beam, a theoretical laser cutting model is also introduced to analyze and predict the performance of the diode laser source when cutting stainless steel sheet (304). Fusion cutting experiments of these stainless steel sheets with thicknesses ranging from 1 mm to 10 mm are then carried out using the diode laser source. The results of the experiments are in good agreement with the theoretically predicted results. When comparing with the relevant industrial cutting results using the fiber laser, this diode laser source can obtain a greater speed at the thickness of samples above 3 mm.

2. Specifications of diode laser source

In this work, we employ a direct diode laser source based on multi-wavelength multiplexing. The unit devices used in this source are commercially available building blocks that are developed by ourselves. These building blocks are manufactured based on the technology of single-emitter multiplexing, and each building block is equipped with up to nine single emitters that are wavelength-stabilized by use of a common volume Bragg grating (VBG). Because of the diffraction-limited beam quality of these single emitters in fast axis (FA), the nine single emitters are stacked vertically on a shared copper heat sink. Due to the demand for dense spectral multiplexing (DSM), various wavelengths VBGs are used to stabilize the output radiations from these building blocks at different wavelengths. The output radiations from the five building blocks are then dense spectrally multiplexed using reflective VBGs. Subsequently, after DSM, the multiplexed output radiations experience polarization multiplexing to double its power and brightness at a constant beam quality. Similar results are obtained from three diode laser modules that lased at 91× nm, 94× nm and 97× nm. All the wavelength channels are listed in Table 2.

Finally, the three diode laser modules are coarse spectral multiplexed using dielectric filters. A schematic diagram of the complete diode laser source is shown in Fig. 1.

The output beam after coarse spectral multiplexing is coupled into a commercially available quartz block high-power (QBH) fiber with a 105 µm core diameter and a NA of 0.2. At a coolant temperature of 25 °C and in a continuous wave (CW) operating mode, the diode laser source can produce 2045 W power from the output fiber at an injection current of 10 A. The corresponding beam quality is measured using a Primes focus monitor, which is shown in Fig. 2. Details with regard to the design and the characteristics of this diode laser source (listed in Table 3) are presented in [10].

3. Theoretical analysis

3.1. Theoretical model based on absorption calculations

In laser cutting applications, the polarization state of the incident laser beam plays an important role for the absorption in metallic surfaces [11]. The average absorptivity is directly dependent on the polarization state of the incident laser radiation. The Fresnel equations for opaque metals give the relationships between the inclination angle θ_I, the reflectivities R_P and R_S for parallel and perpendicular polarized radiation, respectively [12]:

$$R_P = \frac{(n\cdot\cos\theta_I - 1)^2 + (\kappa\cdot\cos\theta_I)^2}{(n\cdot\cos\theta_I + 1)^2 + (\kappa\cdot\cos\theta_I)^2} \tag{1}$$

$$R_S = \frac{(n - \cos\theta_I)^2 + \kappa^2}{(n + \cos\theta_I)^2 + \kappa^2} \tag{2}$$

where n is the refractive index, and κ is the extinction coefficient [13]. These two optical parameters are both functions of the permittivity ε, based on the following relationships:

$$n = \left(\frac{(\varepsilon_1^2 + \varepsilon_2^2)^{1/2} + \varepsilon_1}{2}\right)^{1/2} \quad \text{and}$$

$$\kappa = \left(\frac{(\varepsilon_1^2 + \varepsilon_2^2)^{1/2} - \varepsilon_1}{2}\right)^{1/2} \tag{3}$$

Here, ε_1 is the real part and ε_2 is the imaginary part of the permittivity [14]. These quantities can then be calculated using Eq. (4):

$$e_1 = 1 + \frac{w_P^2}{\omega_L^2 + \nu_C^2} \quad \text{and}$$

$$\varepsilon_2 = \frac{\nu_C}{\omega_L}\cdot\frac{\omega_P^2}{\omega_L^2 + \nu_C^2} \tag{4}$$

In the upper equation, ω_P is the plasma frequency, ω_L is the laser frequency and ν_C is the collision frequency. Using the theory that was presented in [15], these parameters are calculated for iron, which acts as a substitute for the stainless steel. Consequently, the corresponding values of the refractive index n and the extinction coefficient κ for the central wavelengths of the three diode laser modules are calculated and listed in Table 4.

In this diode laser source, the output radiation consists of beams with parallel and perpendicular polarizations, and the power of these two parts of the beam are approximately equal. Therefore, an approximation of the average absorptivity A_{Ave} in the metal sheet can be expressed as follows:

$$A_{Ave} = 1 - R_{Ave} = 1 - \frac{R_P + R_S}{2} \tag{5}$$

Table 2
Stable wavelength channels of three diode laser modules.

	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5
Module 1 (91× nm)	913.1	914.5	916.0	917.6	919.0
Module 2 (94× nm)	941.3	942.7	944.4	945.8	947.3
Module 3 (97× nm)	972.8	974.5	976.1	977.5	979.0

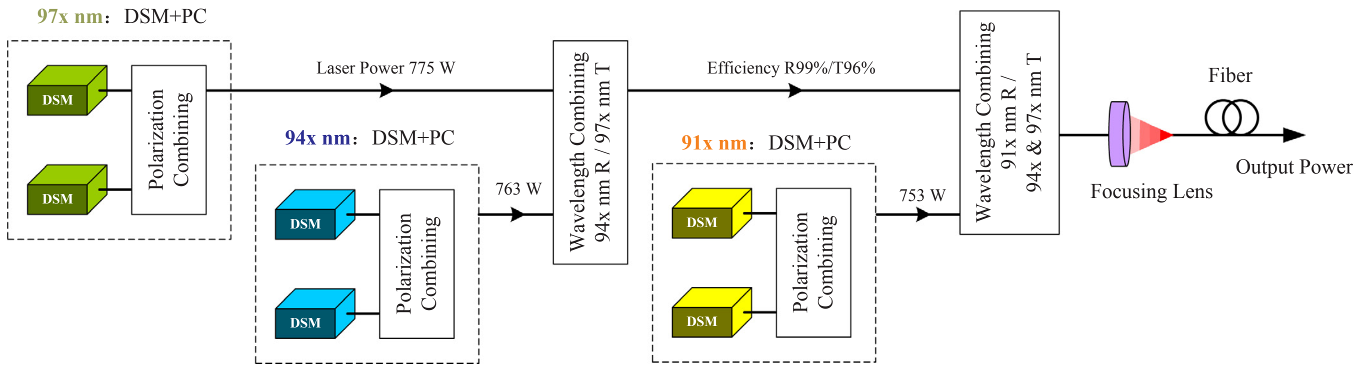

Fig. 1. Schematic diagram of the complete diode laser source.

The calculation of average absorptivity should take the wavelength differences into account, so for the diode laser source based on multi-wavelength multiplexing, the metallic absorptivity can be obtained by using weight calculation of the output power of the three modules:

$$A_{DL} = \frac{A_{\lambda_1}\cdot P_1 + A_{\lambda_2}\cdot P_2 + A_{\lambda_3}\cdot P_3}{P_1 + P_2 + P_3} \quad (6)$$

Here, $A_{\lambda 1}$, $A_{\lambda 2}$ and $A_{\lambda 3}$ are the average absorptivity at the center wavelengths of three modules, which are listed in Table 4. Based on the above equations, the relationship between the inclination angle θ_I and the average absorptivity A_{Ave} for the diode laser source is plotted in Fig. 3. The average absorptivity reaches an obvious maximum at 79°, which is referred as the Brewster angle. The corresponding curve for the fiber laser source is also added to Fig. 3, and the figure shows a slight deviation between the Brewster angle of the diode laser source and that of the fiber laser source because of their wavelength difference.

Table 3
Beam parameters of diode laser source.

Specifications and measured characteristics	Unit	Value
Optical fiber	[μm]	105
NA	—	0.2
M^2	—	35
BPP	[mm mrad]	10.5

Table 4
Refractive index n and extinction coefficient κ for three wavelengths at melting point temperature.

	λ_1 = 916.0 nm	λ_2 = 944.4 nm	λ_3 = 976.1 nm
n	5.11	5.18	5.25
κ	3.52	3.61	3.70

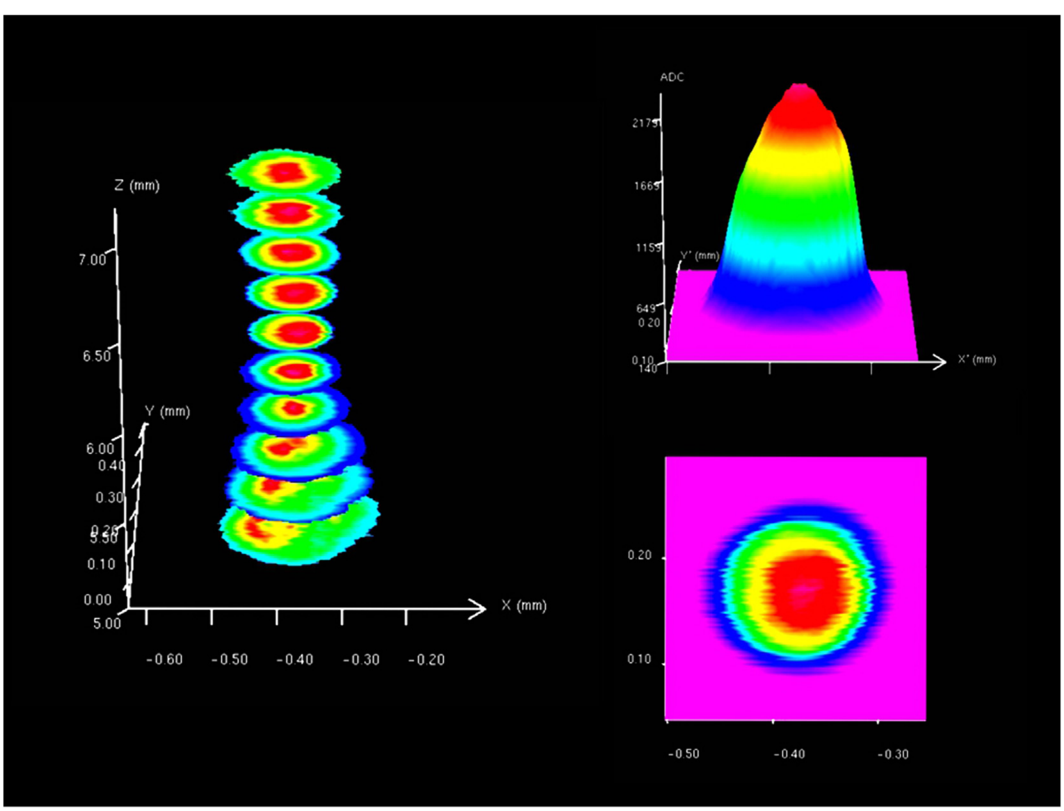

Fig. 2. Beam quality measured by Primes focus monitor at I = 10 A.

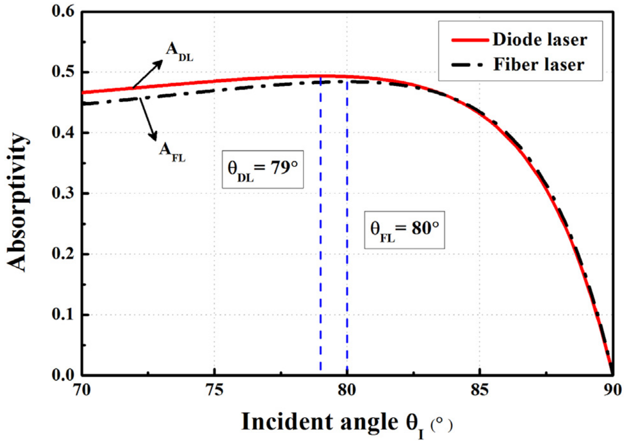

Fig. 3. Absorptivity as a function of inclination angle θ_I.

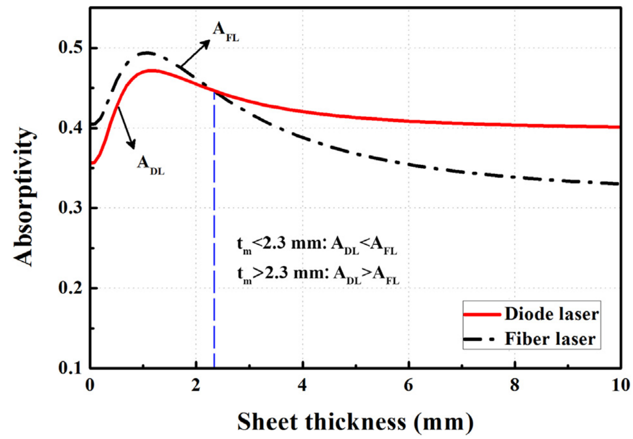

Fig. 5. Calculated absorptivity of diode laser A_{DL} and fiber laser A_{FL} vs. sheet thickness t_m.

3.2. Theoretical diode laser cutting performance

The absorptivity as a function of the inclination angle, which is calculated in the previous section, demonstrates the importance of the cut front profile to the efficiency of the cutting process. In this test, we use a simple two-dimensional model deduced from the beam shape (Fig. 4) [16] to obtain a rough approximation of the inclination angle θ_I.

From this two-dimensional model, the inclination angle θ_I can be calculated by the sheet thickness t_m, the focus position f_p and the beam radius at the top (r_T) and the bottom (r_B) of the sheet surface:

$$\theta_I = \arctan\left(\frac{t_m}{r_T(t_m, f_p) + r_B(t_m, f_p)}\right) \tag{7}$$

Through the calculation from Eqs. (1)–(7), the absorptivity of the two laser sources is plotted as a function of sheet thickness in Fig. 5. The absorptivity for the diode laser source is greater than that for the fiber laser source when the thickness of stainless steel sheet exceeds 2.3 mm.

To obtain the achievable cutting speed of the diode laser source, the requirement of laser power should also be considered. The amount of material that is removed via laser cutting is closely related to both the laser power and the beam waist. If the assumption is made that all absorbed power is used to melt the metal material, the following simple equation can be derived for the cutting speed:

$$v_C = \frac{P_L}{t_m \cdot d_0 \cdot \rho_m \cdot \Delta h_m} \tag{8}$$

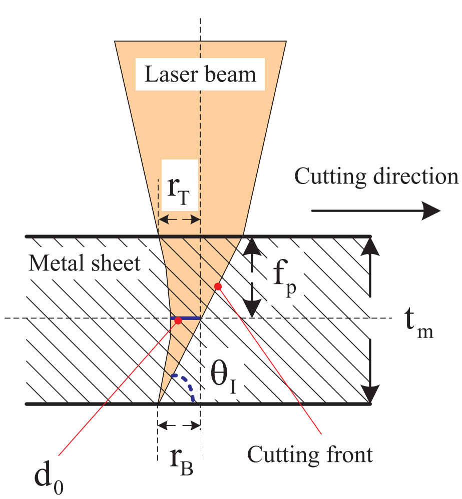

Fig. 4. Two-dimensional diagram of laser cutting of metal sheet.

where P_L is the operational laser power, t_m is the sheet thickness, d_0 is the diameter of the beam focusing point, ρ_m is the material density and Δh_m is the increase in specific enthalpy required to cause melting of the material to be cut when starting from the ambient temperature ($1174\ \mathrm{kJ \cdot kg^{-1}}$ for stainless steel). We select stainless steel sheets with thickness ranging from 1 mm to 10 mm.

4. Cutting test experiments

During the practical experiments, the diode laser source is integrated into a cutting machine. Fig. 6 shows a schematic diagram of the laser cutting set-up. The diode laser source is connected to the cutting head via an optical fiber. The cutting head is equipped with an aspheric collimator that has a focal length of 125 mm and an aspheric focusing lens with a focal length of 125 mm. Such lens matching can make the cut front angle of incident beam more close to the Brewster angle which is calculated in Section 3.1. The optical power at the workpiece can reach 1960 W. The main loss mechanisms of power can be explained as follows:

- The step of transmission in the cutting head leads to a certain power loss, which is mainly because that each surface of the aspheric collimator is covered by an antireflective film that has a residual reflectance of 0.5%, and the accumulation of small imperfections in the coating results in a relatively high power loss of approximately 2%.
- Because of the aberration characteristics of the aspheric lens in the cutting head, some marginal rays deviate from their expected path

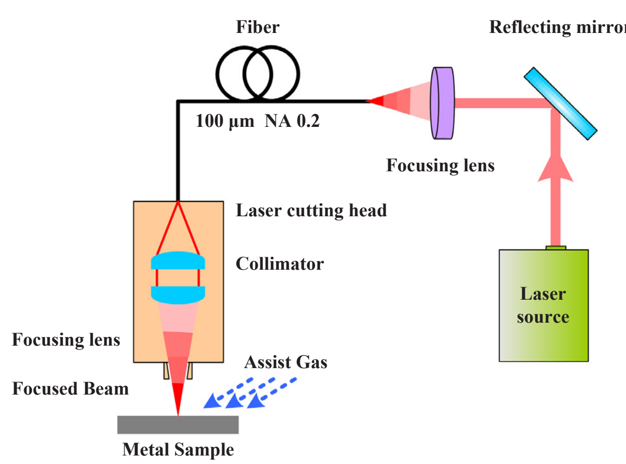

Fig. 6. Schematic diagram of the cutting machine.

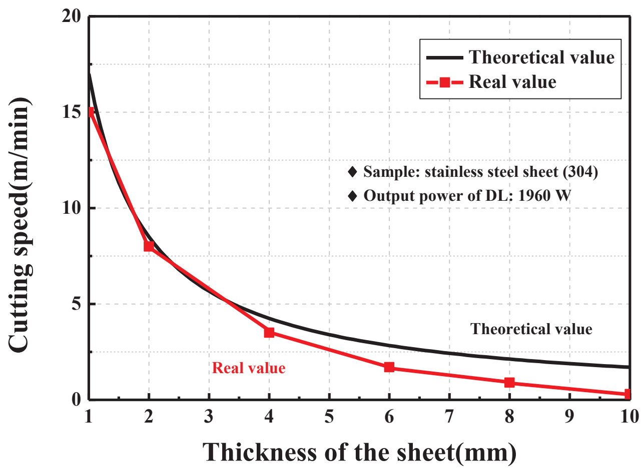

Fig. 7. Theoretical maximum cutting speed vs. sheet thickness.

after collimation and focusing which can then be cut by the nozzle of the cutting head.

Stainless steel sheets (304), the most commonly used material in industry, with thicknesses of 1 mm, 2 mm, 4 mm, 6 mm, 8 mm and 10 mm are selected for the cutting experiment. Standard diode laser cutting parameters are used in the test. The nozzle diameter is 2 mm, and the N_2 cutting gas pressure is 12 bar. To obtain the optimal achievable cutting results, the focal point position is adjusted to the middle of the stainless steel sheets during the cutting process.

5. Results and discussion

Using the experimental system and cutting parameters described above, stainless steel sheets with thicknesses ranging between 1 mm and 10 mm are cut successfully, and the cutting results are plotted in Fig. 7. From the diagram, we see that the actual cutting speed is slower than the theoretically calculated speed, which can be explained as follows:

- During the cutting experiments, the heat input affects the cutting speed directly, so the effects of thermal losses should be taken into account. Because of reflection from metallic surfaces, a small portion of the laser power P_L can only be lost during the cutting process via thermal conduction to the surrounding base material, which is inversely proportional to cutting speed. As the thickness of stainless steel sheets increases, the cutting speed decreases and thermal conduction losses rise.
- During the laser cutting process, the assisted gas takes part of the energy away, which results in thermal loss from the molten zone and decreases the cutting speed.

In addition, the actual power loss of the transmission in the cutting head can also lead to a deviation between the actual and theoretically predicted values.

We now compare the optimized cutting speed of the diode laser source with that of fiber laser. The values of cutting by using 2 kW-class fiber laser source was presented in [17]. The fiber laser used are emitting around 1.06 μm, and the output fiber is 100 μm. The M^2 and BPP are 9.92 and 3.377, respectively. The beam spot radius is 0.064 mm, when a group of collimating lens and focusing lens both with a focal length of 100 mm are utilized. Results of this comparison are presented in Fig. 8 (a). As expected, the diode laser source and the fiber laser show a similar trend with the increase of thickness because of their approximate wavelengths. However, for the thickness of stainless steel sheets (1 mm ≤ d ≤ 2 mm), the cutting speed of fiber laser is faster than that of diode laser, and the diode laser shows a faster speed at the thickness above 4 mm (d ≥ 4 mm). From Fig. 5, we can know that absorptivity of diode laser and fiber laser has a crossover point at the thickness of 2.3 mm. So even though the cutting test of 3 mm stainless steel sheet is not carried out in the experiment, we also consider that two types of lasers have an almost identical speed around 3 mm. The cutting edge roughness (Rz) measured with a profilometer shows that the Rz of samples cut by diode laser source is below 10 μm at the thickness from 1 mm to 4 mm, which is better than that (Rz = 30 μm) of samples cut by fiber laser at the same thickness. The roughness deteriorates with the increase of thickness, but diode laser can obtain better results across the entire thickness range.

These results demonstrate that the diode laser source generates a shorter wavelength than the fiber laser, which leads to a better absorptivity for the stainless steel sheets. Fig. 8(b) shows images of the

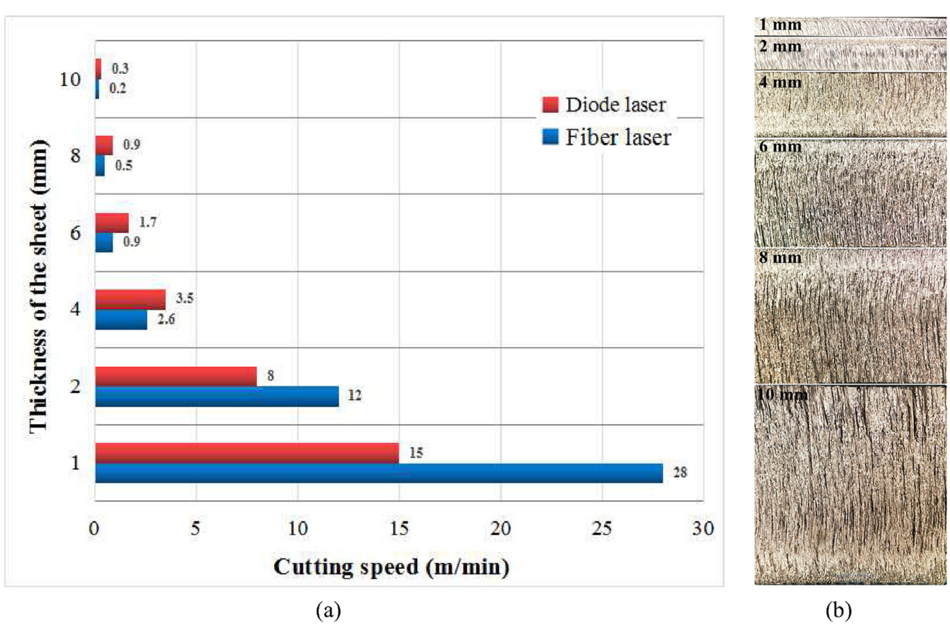

Fig. 8. (a) Comparison results of two laser sources at an optimized cutting speed (m/min) for stainless steel (304). (b) Images of the sheet cutting edges cut by the diode laser source.

edges of samples that are cut by the diode laser source. Comparing with past diode laser sources, the beam quality of the diode laser source here has a approximately 10 times increase because of the technical improvement of beam multiplexing, which makes it possible for the diode laser source to be used in laser cutting applications.

6. Summary and conclusions

A novel diode laser source based on a state-of-the-art building block platform that produces an output power of 2045 W from an output fiber with a 105 μm core diameter and a NA of 0.2 is introduced in this paper. According to the results of absorption calculations and the characteristics of the multi-wavelength diode laser source, a laser cutting theoretical model is established to predict the cutting performance. Using this diode laser source, stainless steel sheets with thicknesses of between 1 mm and 10 mm were cut successfully. Comparing with industrially relevant results of cutting using fiber lasers, this diode laser source can obtain a greater speed at the thickness of samples above 3 mm. This work not only demonstrates the feasibility of diode laser source for high-speed laser cutting in industry, but also provides theoretical guidance for future research of diode laser source cutting applications.

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