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ORIGINAL ARTICLE

Continuous-wave laser drilling assisted by intermittent gas jets

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Abstract We describe a study of the laser drilling of stainless steel (SUS304) using a fiber laser with a wavelength of 1090 nm, assisted by intermittent gas jets. By comparing with the results obtained with the conventional continuous gas jets used in assisted laser drilling, we demonstrate that the use of the intermittent gas jets can effectively increase the material removal rate and reduce the consumption of assist gas. The intermittent gas jets can be modulated according to the frequency to effectively reduce the overcooling effect of the assist gas. Experimental results show that both the drilling depth and machining quality can be greatly and simultaneously improved. Two types of intermittent gas jets, namely, straight and swirling jets, are considered, and the effects of the intermittent frequencies and gas pressures on the laser drilling are investigated and discussed. We conclude that the intermittent gas jet method greatly reduces heat loss and slag formation around the hole exit in the laser drilling process. Compared with the results obtained when using a continuous straight gas jet, laser drilling with a 20-Hz intermittent straight gas jet reduces the drilled hole entrance diameter and increases the drilled hole depth by a factor of up to 1.7. The intermittent gas jet method can reduce the quantity of assist gas being used, and therefore the cost, especially when expensive gases such as helium and argon are being used.

Keywords Intermittent gas jets · Continuous-wave laser · Laser drilling

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1 Introduction

Many technological advances have been made in the field of laser drilling [1–4]. Laser drilling is a non-contact machining process in which a laser beam is focused onto a spot to produce sufficient power densities to melt or even vaporize the surface material and thus form a hole. It is capable of drilling high-quality holes with large aspect ratios at a high machining rate in a variety of materials [5–10]. To achieve a high machining rate, high-pressure gas jets are commonly used to assist with the laser drilling. The high pressure of these gas jets causes molten material to be ejected from the hole during laser drilling so that the material removal efficiency is increased [11]. Typically, the gas jets are supplied continuously, and the gas pressure is controlled to minimize the possible side effect of cooling by the gas, as any such cooling could adversely affect the laser drilling efficiency. Therefore, the use of continuous gas jets with laser drilling incurs the problem of the molten material being overcooled such that it cannot be ejected from the hole during drilling. The rebounding gas flows carrying the molten slag and the laser-induced plume from the hole being processed may also shade the laser beam and thus reduce the processing efficiency [5, 11, 12]. Many methods have been adopted as a means of eliminating the interference of the laser-induced plume during laser machining. For example, magnetic and electrical forces have been applied to attract or repel the charged particles in the laser-induced plume in an attempt to accelerate its dissipation [13–17]. A considerable amount of research has been carried out with the goal of devising an efficient gas jet-assisted material-ejection mechanism that could be applied to laser drilling. Tsai and Lin [18] characterized plume particle removal through laser ablation by using a swirling-flow nozzle. Their results showed that the laser-induced plume can be removed efficiently and that the surface roughness could be reduced significantly by implementing a swirling flow during the laser ablation. Chen et al. [19] reported on a modeling study of the gas flow in laser machining and studied the interaction of a supersonic, turbulent axis-symmetric jet with the workpiece. Khan et al. [12] reported on the machining rates and hole quality that could be attained with nanosecond laser percussion drilling of 200-mm 316L stainless steel, as performed with supersonic gas jets produced using nozzles with 200-, 300-, and 500-mm nominal throat diameters. Khan et al. [20] studied the use of high-pressure gas jets in the laser drilling process and demonstrated that they had a significant influence on the melt ejection mechanism. Their simulations predicted the formation of broad-spectrum surface pressure fluctuations due to both the turbulent nature of the gas jet and the blunt shock oscillation on the surface. On the other hand, in order to understand the thermal phenomena and temperature fields, several models for the laser drilling process have been reported in the literature [21–27]. For example, Chan and Mazumder [21, 22] used multiphase model with the heat equation to analytically analyze the evaporation and melt expulsion and discuss the material removal rates. Pastras et al. [23] used the heat equation to numerically model the temperature field and energy efficiency of pulsed laser drilling. Leitz et al. [24] employed the transport equations and energy-based heat conduction equation of the fluid dynamics for the multiphase system to look into the drilled hole during the ablation process with short laser pulses.

In this paper, we propose the utilization of intermittent gas jets to assist with the laser drilling of stainless steel sheets. To the best of our knowledge, the effectiveness of using intermittent gas jets with laser drilling has not been investigated elsewhere. An intermittent-pressure gas jet is applied during laser drilling such that the molten material is ejected, also intermittently, from the processing hole. The intermittent frequency of the gas jet can be tuned to control the timing at which the molten material is ejected. While a gas pulse is not being applied, the laser energy accumulation for ablating the material becomes much more efficient. The overcooling issue incurred by the high-pressure continuous gas jet method can thus be managed, and the degree of laser beam shading caused by the plume can also be reduced. Higher efficiency melt ejection during laser drilling can be achieved by using higher pressure intermittent gas, which suppresses the issue of overcooling.

2 Machining mechanisms and experimental details

The absorptivity A of a material subject to laser irradiation is one of the most important parameters influencing laser–material interaction. For opaque materials, the absorptivity at the normal incidence can be expressed as [28]

$$A = 1-R, \tag{1}$$

where R is the reflectivity, defined as

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}. \tag{2}$$

In Eq. (2), n and k are the refractive index and extinction coefficient, respectively, which strongly depend on the wavelength and temperature. The reflectivity of steel towards laser radiation with a 1090-nm wavelength is about 60 % and increases with the wavelength of the laser being used. The effects of laser–material interaction include heating, surface melting, surface vaporization, plasma formation, and ablation. Generally, these phase transformations are associated with threshold laser intensities (i.e., melting and evaporation thresholds). Laser drilling without any gas jet assistance involves all the phase transformations in the material being removed. On the other hand, the application of gas jet assistance during laser drilling increases the material removal rate by ejecting most of the surface material at the melting phase, which improves the machining efficiency. Typically, the gas jets are applied continuously, and the gas pressure is tuned to optimize the material removal rate. However, this method lacks a tunable parameter for controlling the material ejection time, and the cooling effect of the assist gas may considerably limit the material removal rate. Therefore, the intermittent gas jet assistance proposed here supports timing control.

To give a basic understanding of the temperature field of the laser drilling, we summarize and discuss the time-dependent equations that govern the heat transfer of multiphase systems. More detailed discussion can be found in refs. [21–23]. According to the process of laser irradiation without any gas jet assistance, the workpiece experiences heating, melting, and vaporization phases from the viewpoint of hear transfer. During the heating phase, the temperature field T of the workpiece along the depth (z direction) can be described by

$$\frac{\partial^2 T(z,t)}{\partial z^2} = \frac{1}{a}\frac{\partial T(z,t)}{\partial t}, \tag{3}$$

where a is the thermal diffusivity of the workpiece. In this phase, the temperature field can be solved with the initial condition

$$T(z,0) = T_0, \tag{4}$$

where T_0 is the initial temperature of the workpiece before the laser is applied. During the laser irradiation, the dominating mechanism of heat transfer in the workpiece is conduction. The boundary condition, therefore, is given by

$$\left.\frac{\partial T(z,0)}{\partial z}\right|_{z=z_0} = -\frac{1}{k_t} I(z_0,t), \quad (5)$$

where k_t is the thermal conductivity of the workpiece material, I is the absorbed power density, and z_0 is the workpiece surface.

When the surface temperature of the workpiece reaches the melting temperature T_m, solid and liquid phases coexist and interchange heat energy. The heat equations for the two regions of solid and liquid are given by

$$\frac{\partial^2 T_i(z,t)}{\partial z^2} = \frac{1}{a_i}\frac{\partial T_i(z,t)}{\partial t}, \quad i = \text{s and l}, \quad (6)$$

where the indices s and l denote solid and liquid phases, respectively. The temperature on the interface of the two regions is the melting temperature T_m; therefore,

$$T_s(z_m(t),t) = T_l(z_m(t),t) = T_m, \quad (7)$$

where $z_m(t)$ is the depth position of the interface separating the solid and liquid regions. The interface is a moving boundary. The moving velocity of the interface is determined by the latent heat of fusion L_f. The associated boundary condition can be described by the so-called Stefan condition:

$$k_s\left.\frac{\partial T_s(z,0)}{\partial z}\right|_{z=z_m(t)^+} - k_l\left.\frac{\partial T_l(z,0)}{\partial z}\right|_{z=z_m(t)^-} = \rho L_f \frac{dz_m(t)}{dt}, \quad (8)$$

where ρ is the mass density. This condition represents the energy conservation at the interface. The boundary condition on the surface $z=z_0$ is the same as that given by Eq. (5) to solve for Eq. (6), and the initial condition is provided by the solution of Eq. (3) in the heating phase.

When surface temperature reaches the vaporization point, the vaporization begins. The governing equations are the same as Eq. (6). However, another interface at $z=z_v(t)$ forms further to separate the liquid and gaseous phases. Similar to the approach used in the melting phase, the temperature on the interface of the liquid and gaseous regions is the vaporization temperature T_v; therefore,

$$T_l(z_v(t),t) = T_v, \quad (9)$$

and the second moving boundary condition at liquid and gaseous interface $z_v(t)$ is

$$k_l\left.\frac{\partial T_l(z,0)}{\partial z}\right|_{z=z_v(t)^+} + I(z_v(t),t) = \rho L_v \frac{dz_v(t)}{dt}, \quad (10)$$

where L_v is the latent heat of vaporization. The initial condition is provided by the solution of the melting phase.

The numerical solutions of the three phases of laser drilling for the temperature fields can be found in ref. [23]. In relation to the gas jet assistance, the gas jet gives an additional momentum to remove the material during the melting and vaporization phases and interrupts the heat transfer process by ejecting the material. The gas jet possibly also adds the cooling effect to the molten and vapor during the laser irradiation by absorbing the heat energy. Our intermittent gas jet method provides reduced cooling effect and efficient molten ejection.

Stainless steel SUS304 sheets with thicknesses of 500 and 1000 μm were used as the workpieces. The sheets were drilled using a fiber-optic-delivered 45-W continuous-wave (CW) laser with a wavelength of 1090 nm (SPI, redPOWER fiber laser). Air was used as the assist gas in the experiments. The laser drilling of blind holes (drilled in the 1000-μm sheets) and through holes (drilled in the 500-μm sheets) was attempted in the experiments. Each experiment was repeated three times, and the mean value of the three measurements was used as the output for each set of parameters.

A schematic of the experimental setup is shown in Fig. 1. The apparatus was set up on the platform of a high-precision machining center (Sodick, AQ35L Electric-Discharge Machine). Optical fiber is used to transfer the light from the laser system to the focal lens. The workpiece was fixed in an XY micro stage. The laser beam was focused onto the surface of the workpiece. The focal length was 150 mm. A gas nozzle was placed between the focal lens and the workpiece to supply the assist gas (air in this study). The gas nozzle and the laser

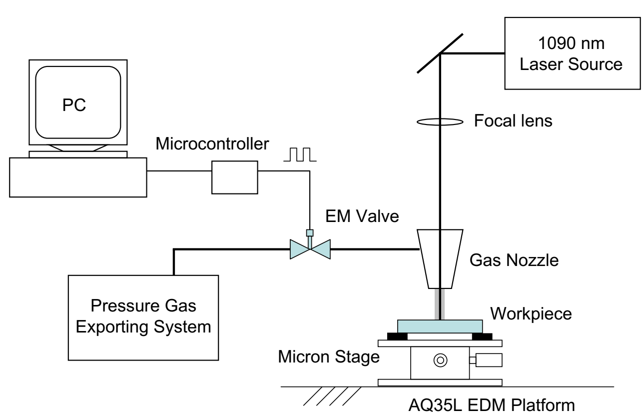

Fig. 1 Schematics of the experimental setup of intermittent gas jet-assisted CW laser drilling

beam were oriented coaxially to impinge on the same point on the workpiece. The pressure of the assist gas was controlled by a gas exporting unit, and the pressurized assist gas was delivered to the nozzle unit through an electromagnetic (EM) valve (Shako, AM520-01-S). The switching frequency and opening duration of the EM valve were controlled by a Darlington circuit and a single-chip microcontroller (PIC 18F4520), via a computer. The on and off times were set to equal values during EM valve switching.

The overall structure of the nozzle used to supply the gas jets is shown in Fig. 2. The gas nozzle unit is shown in Fig. 2a. It consists of a main body, top cover, optical window (made of quartz glass with a transparency of 92 %), gas inlet joint, and nozzle. To generate a swirling gas jet, a rotor was added to the nozzle. The design of the rotor-equipped nozzle is shown in Fig. 2b. The rotor is spun by the pressurized gas which then leaves the exit as a swirling flow. The pressurized gas is delivered via an inlet with a diameter of 1.5 mm, into the gas chamber of the main body. The gas chamber is a cylindrical space with a diameter and height of 20 and 30 mm, respectively. The nozzle is screwed into the main body. The screw part of the nozzle has an outer diameter D and length h of 12 and 6.4 mm, respectively. The diameter d and height H of the empty cylindrical space in the nozzle were 8 and 12.8 mm, respectively. The rotor for generating the swirling gas jet has an inner diameter d_1=3.5 mm, an outer diameter d_2=5 mm, and a flange diameter d_3=8 mm. Twelve circular holes with a radius r=0.4 mm are formed in the rotor flange to guide the pressurized gas into the rotor blades. The exit from the gas nozzles was 0.4 mm in diameter with a length h_3=1.2 mm. The nozzle–material stand-off distance (i.e., the distance from the nozzle exit to the workpiece surface) was set to 1.0 mm in the experiments. Table 1 lists all of the specifications and parameters applied in the laser drilling experiments of this study.

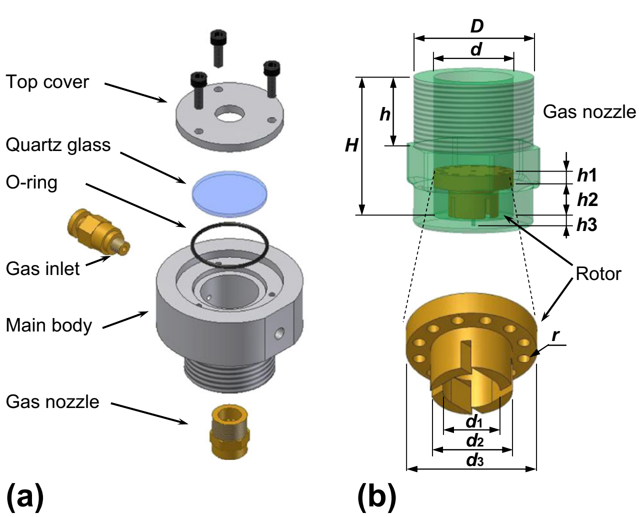

Fig. 2 **a** Assembly of the gas nozzle unit. **b** Design of the gas nozzle with a rotor in addition inside for generating swirling gas jet

Table 1 Specifications and parameters used in the experiments

Specification/parameter	Description
Laser head model	SPI redPOWER
Laser type	Fiber laser
Laser wavelength	1090 nm
Operation mode	CW
Average power	45 W
Processing time (blind holes)	40 s
Focal length	150 mm
Workpiece material	SUS 304 stainless steel
Workpiece thickness	1000 μm (blind holes)
	500 μm (through holes)
Assist gas	Air
Gas pressure	200–800 kPa
Gas jet types	Continuous, straight
	Continuous, swirling
	Intermittent, straight
	Intermittent, swirling
Nozzle–material stand-off distance	1.0 mm
Gas nozzle exit diameter	0.4 mm
Intermittent frequency	10 and 20 Hz
Intermittent gas on/off time ratio	1:1

3 Results and discussion

Laser drilling of SUS304 sheets with thicknesses of 1000 and 500 μm was performed in CW mode to create blind holes and through holes, respectively. The effects of the assist gas parameters (i.e., gas pressure and intermittent frequency) on the mean values of the laser drilled hole depth and average hole diameter are examined below. The average hole diameter D_{ave} is given by

$$D_{ave} = \frac{D_{max} + D_{min}}{2}, \quad (11)$$

where D_{max} and D_{min} are the maximum and minimum diameters of the hole, respectively. The morphology of the drilled materials was analyzed by using an optical microscope (Modal No: Olympus STM U-PMTVS 8C14561). In practicing the measurement, the hole diameters were measured using the built-in measuring function provided by the optical microscope with a CCD camera. By rotating the workpiece, the longest and shortest distances as the diameters of two circles to ring the boundary of a hole entrance or exit were determined. The measured diameters of two circles were used as D_{max} and D_{min}, respectively. The single experimental hole diameter D_{ave} was calculated using Eq. (11). Each experimental diameter value was the average of hole diameters obtained by three drilling experiments. The quality (or straightness) of the laser-drilled through hole can be determined from the taper angle α of the hole. The taper angle of the hole can be calculated as

$$\alpha = \frac{D_{\text{entr}} - D_{\text{exit}}}{2h} \times \frac{180}{\pi}, \tag{12}$$

where D_{entr} is the hole entrance diameter, D_{exit} is the hole exit diameter, and h is the material thickness.

3.1 Blind hole drilling using laser assisted by intermittent straight gas jet

Figure 3 shows cross sections of the laser-drilled blind holes produced in the 1000-μm SUS304 stainless steel sheet with different gas pressures (from 200 to 800 kPa) and different intermittent frequencies of the gas jets (10 and 20 Hz). The results of using continuous and intermittent gas jets are also compared in the figure. The laser machining time was 40 s. From the figure, we can see that the laser drilling depths are significantly improved when using the intermittent gas jet for assistance. The depth increases with the assist gas pressure. When using a continuous gas jet, however, the drilling depth decreases slightly as the gas pressure is increased. This shows that the intermittent gas jet method effectively eliminates the cooling effect of the gas jets during laser drilling. In this case, the laser ablation efficiency is improved, while increasing the gas pressure maintains the molten material ejection rate and thus increases the drilling depth. Figure 4 shows the variation in the drilling depth as a function of the gas pressure. It can be seen that increasing the intermittent frequency from 10 to 20 Hz further improves the drilling depth, showing that the efficiency of the melt ejection mechanism still dominates the cooling effect with the 20-Hz intermittent gas jet assistance. That is, the molten material ejection rate and drilling

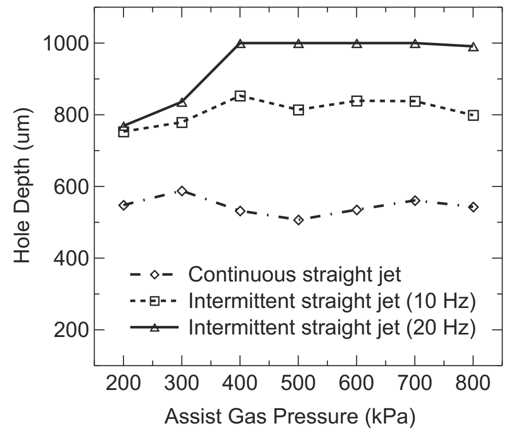

Fig. 4 Laser-drilled hole depth as a function of gas pressure for the cases of continuous straight gas jet and 10- and 20-Hz intermittent straight gas jets assisting

efficiency continue to increase with the intermittent frequency without overcooling the material. Note that for high gas pressures of 500, 600, and 700 kPa and the 20-Hz intermittent gas jet assistance, through holes can be produced in the 40-s laser machining time. In these cases, the application of the 20-Hz intermittent straight gas jet to laser drilling increases the drilling depth by a factor of up to 1.7.

In our laser-drilling process with the pressurized air as the assist gas, oxidization should be involved. The oxidation phenomena are complicated and influential in laser machining [28]. For example, oxidizing gases (e.g., oxygen) provide heat of oxidization released by the exothermic reaction to improve the machining efficiency (the amount of such energy could be significant for laser machining assisted by oxidizing gases) and formation of oxide layers. The metal oxides might also have higher or lower viscosity to impede or facilitate the ejection of molten material from the machining zone. Typically, proper gas mixtures (e.g., mixture of nitrogen and clean dry air

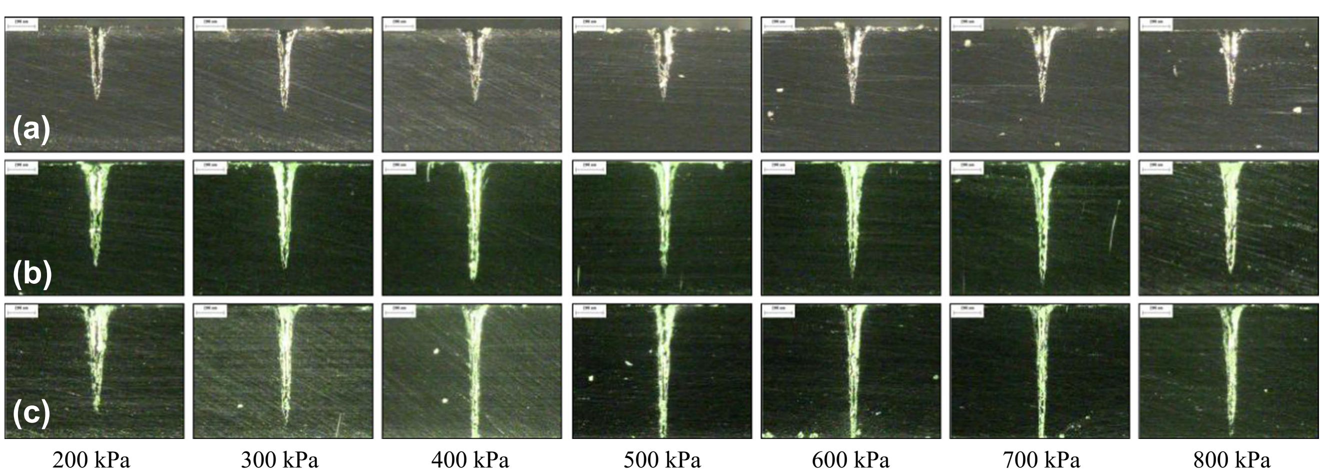

Fig. 3 Cross-sectional views of the laser-drilled blind holes assisted by **a** continuous straight gas jet, **b** 10-Hz intermittent straight gas jet, and **c** 20-Hz intermittent straight gas jet, respectively. Some of the laser-drilled holes with the 20-Hz jet are through the sheets in the 40-s machining time (at assist gas pressure equal to 400, 500, 600, and 700 kPa)

for stainless steel and aluminum) are used to minimize the undesirable effects, such as the oxidization of the heat-affected zone (HAZ) and plasma interference. In our experiments, a wide range of gas pressure was considered. In the low gas pressure regime, cooling effect is minor so the laser-drilled depth improvement is mainly contributed by the efficient ejection mechanism of the intermittent gas jet. When the gas pressure is high, exothermic reaction and cooling effect are competitive. The intermittent gas jet assistance lowers the cooling effect with efficient material ejection maintained to increase the machining efficiency.

3.2 Blind hole drilling using laser assisted by swirling gas jet

In this subsection, we analyze the application of continuous and intermittent swirling gas jets to assist laser drilling. Figure 5 shows cross sections of blind holes drilled with continuous and intermittent swirling gas jets at different gas pressures. In every case, the machining time was fixed to 40 s. The results can be compared with those obtained with straight gas jets. With the continuous swirling gas jet, the images in Fig. 5a show that the drilling depth is increased in most cases, and the average hole diameter is reduced, as is the amount of spatter. The swirling gas jet is better able to disperse the ejected material and produces a smaller cooling effect than the straight jet when gas is supplied continuously over the studied pressure range. Figure 6 compares the variations in the laser drilling depth (mean values of three measurements) as a function of the gas pressure with continuous straight and continuous swirling gas jets. Both the machining efficiency (as determined by the depth) and hole quality (determined by the entrance diameter) are improved with the use of the swirling gas jet.

For the intermittent swirling gas jet, the results of our experiments are shown in Fig. 5b, c. A similar result to that obtained when using intermittent straight gas jets is observed. The holes produced with the intermittent swirling jet are obviously deeper (as attained with a machining time of 40 s). However, the intermittent frequency does not significantly affect the depth in the swirling case. The variation in the drilling depth as a function of gas pressure is shown in Fig. 7. Increasing the gas pressure increases the drilling depth in the same way as when using the intermittent swirling gas jet. This demonstrates that the use of the intermittent swirling gas flow also avoids overcooling; however, the ejection of the molten material, so as to improve the machining efficiency, is improved only by increasing the gas pressure, not by increasing the frequency. A possible reason why increasing the frequency is not effective is that the downward momentum of the swirling gas flow is smaller, so its ability to eject the molten material is limited. An advantage of the swirling gas jets is that their non-zero angular momentum disperses the ejected molten material during laser drilling, rather than ejecting material

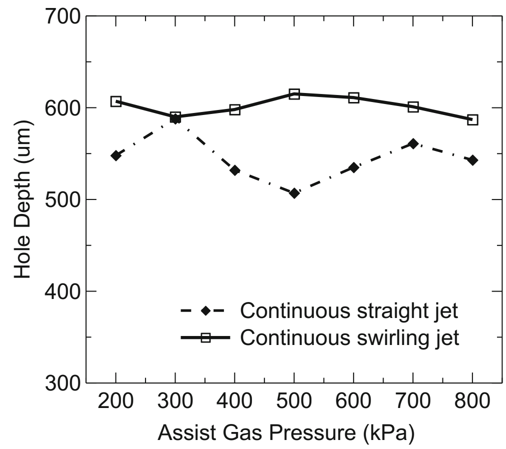

Fig. 6 Laser-drilled hole depth as a function of gas pressure for the cases of continuous straight gas jet and continuous swirling gas jets assisting

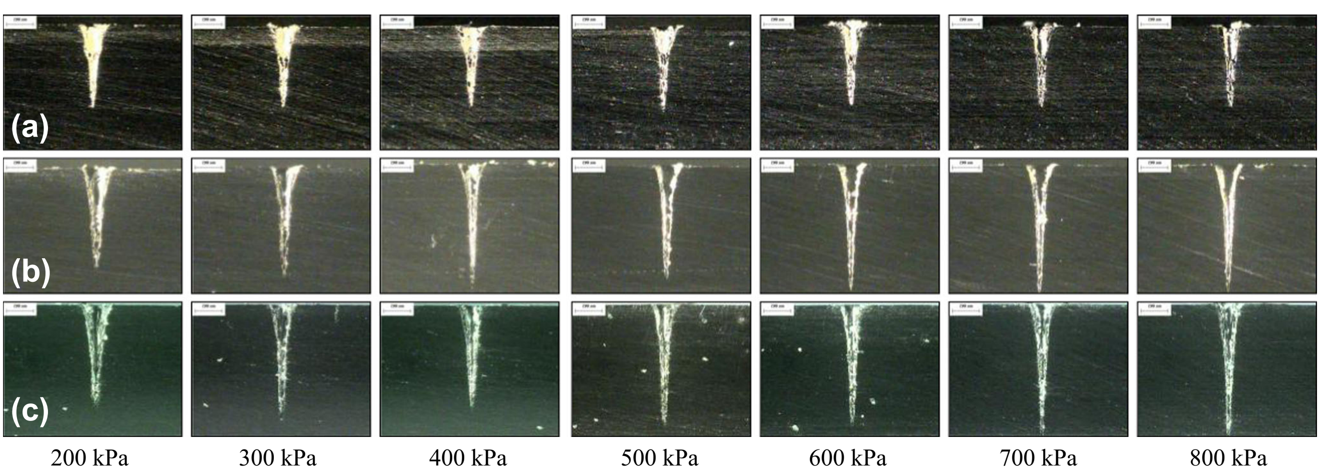

Fig. 5 Cross-sectional views of the laser drilled blind holes assisted by **a** continuous swirling gas jet, **b** 10-Hz intermittent swirling gas jet, and **c** 20-Hz intermittent swirling gas jet, respectively. The laser machining time was 40 s

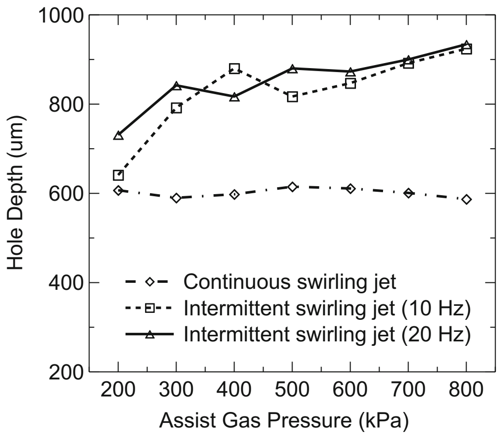

Fig. 7 Laser-drilled hole depth as a function of gas pressure for the cases of continuous swirling gas jet and 10- and 20-Hz intermittent swirling gas jets assisting

from inside the hole, given their reduced downward linear momentum.

3.3 Through hole drilling using laser assisted by intermittent straight gas jet

Figure 8 shows the entrances and exits of laser-drilled through holes produced with continuous and intermittent straight gas jets. The frequencies of the intermittent straight jet were 10 and 20 Hz. The gas pressure was varied from 200 to 800 kPa in increments of 100 kPa. Upon observing the hole entrance, more spatter is found to have been deposited around those holes drilled using the intermittent straight gas jet than around those produced with the continuous straight gas jet. We can assume that the spatter results from the gas pressure being insufficient to disperse the ejected molten material any further. This can be improved by using higher frequency and higher pressure gas jets, as can be seen by comparing Fig. 8b, c. In addition, the continuous gas jet continuously ejected the molten material so the instantaneous material removal by the gas is lower. With the intermittent gas jet, however, more material may be instantaneously removed when a pulse of the intermittent gas jet begins, resulting in more and higher spatter around the drilled holes if the intermittent gas pressure or frequency is not sufficiently high. However, upon increasing the gas pressure, the continuous gas jet produced a cooling effect that prevented the machining temperature from increasing any further. Therefore, we can see, in Fig. 8a, that the spatter height increases. On the other hand, there is less spatter at the exit of the drilled holes when using the intermittent straight gas jet. This is mainly caused by the reduced or discontinuous back pressure around the hole exit when using the intermittent gas jet. For a continuous gas jet, however, a constant low pressure and higher back pressure are produced around the exit, in accordance with the Bernoulli equation of fluid mechanics, so that the molten material is drawn in and accumulates around the exit. It can also be seen that the entrance diameter is reduced and the exit diameter is increased as a result of using the intermittent straight gas jets, in comparison with using the continuous straight jet. In addition, when observing the areas of HAZ on the surfaces of the workpieces, there is no significant difference between using continuous and intermittent straight gas jets.

Figure 9 shows the taper angle α of the laser-drilled through holes, as a function of the gas pressure, as determined using Eq. (12). The taper angle is reduced significantly when using the intermittent straight gas jets. When the gas pressure is less than 500 kPa, the taper angle of a hole drilled with the 20-Hz gas jet is smaller than that produced with the 10-Hz gas jet. With pressures in excess of 500 kPa, however, the taper angle is smaller when using the 10-Hz gas jet. We can conclude that using the intermittent straight gas jets produces a straighter hole profile, as evaluated from the taper angle, than is possible when using the conventional continuous straight gas jet.

3.4 Through hole drilling using laser assisted by swirling gas jet

In this subsection, we first consider the case of through holes that are drilled using a laser assisted by a continuous swirling gas jet. The laser-drilled hole entrance diameters, hole exit diameters, and taper angles are discussed. Figure 10 shows the entrances and exits of the holes drilled with a laser assisted by a continuous swirling gas jet with different gas pressures. The application of the swirling gas jets enhances the hole quality. The entrance and exit diameters are smaller than those of laser-drilled holes produced with the straight gas jets, as shown in Fig. 8. A comparison of the taper angle, as produced with the continuous swirling gas jet and continuous straight gas jet, at different assist gas pressures, is shown in Fig. 11. In both cases, the taper angles basically increase with the gas pressure. The taper angle is also significantly reduced as a result of using the continuous swirling gas jet to assist laser drilling. The use of the continuous swirling gas jet may result in a lower gas pressure around the hole on the top surface of the workpiece, while with the continuous straight gas jet, the gas pressure would be higher. With the swirling jet, this gas pressure difference suppresses the expansion of the hole entrance. Moreover, the backflow velocities are larger around the exit with a continuous straight gas jet, while the taper angle is larger than that produced with the swirling gas jet, in line with the Bernoulli equation. This results in a smaller gas pressure around the hole exit when using a continuous straight gas jet. As a result, it is more difficult to disperse the molten material with the continuous straight gas jet.

We further studied laser drilling assisted by an intermittent swirling gas jet. Figure 12 shows the entrances and exits of

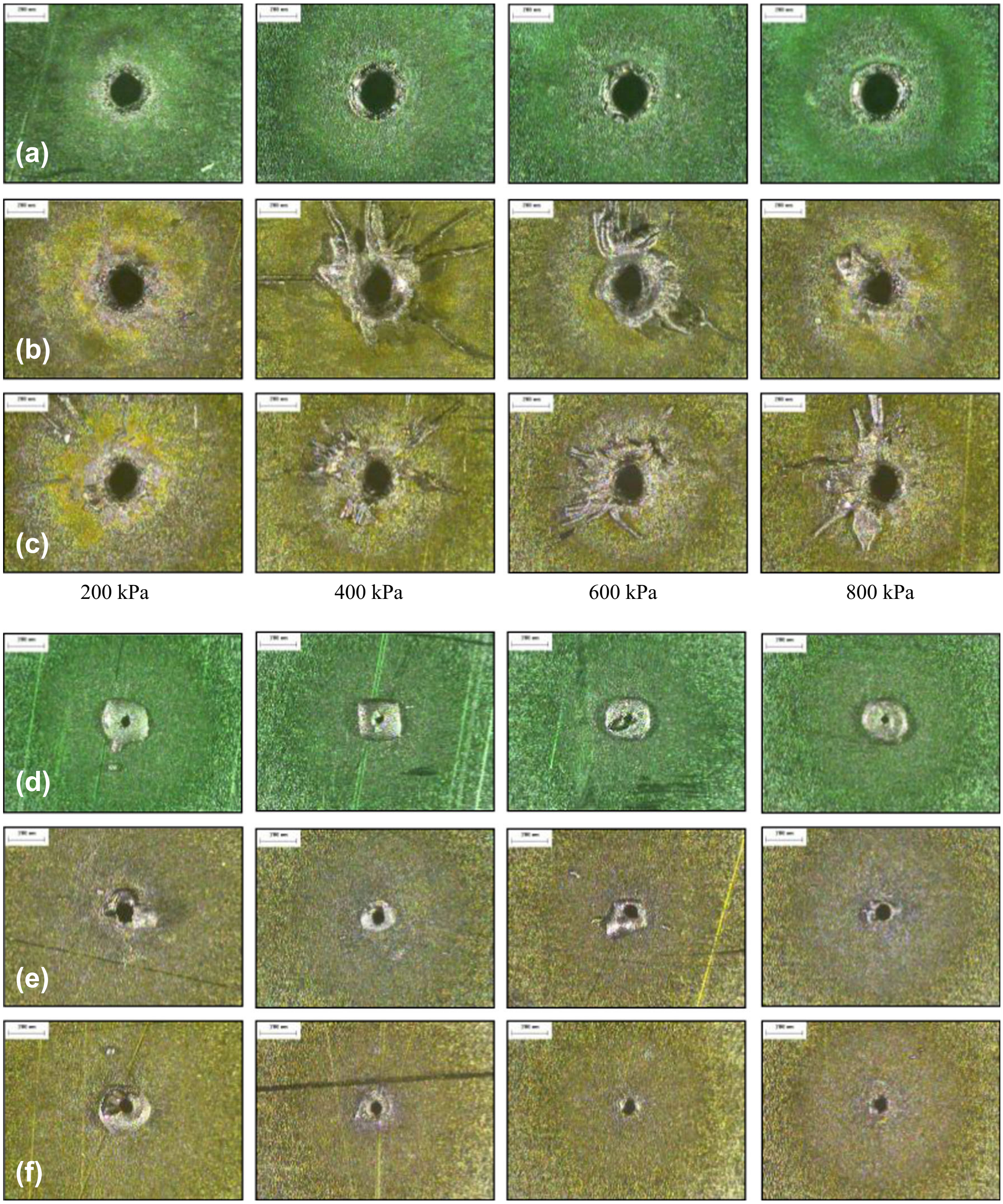

Fig. 8 Entrance of laser-drilled through holes assisted by **a** continuous straight gas jet, **b** 10-Hz intermittent straight gas jet, and **c** 20-Hz intermittent straight gas jet at different gas pressures. Corresponding exit of the laser-drilled through holes with **d** continuous straight gas jet, **e** 10-Hz intermittent straight gas jet, and **f** 20-Hz intermittent straight gas jet at different gas pressures

laser-drilled through holes produced with intermittent straight gas jets. The intermittent frequencies were 10 and 20 Hz. The assist gas pressure was varied from 200 to 800 kPa. The observed spatter formation is similar to that produced when drilling blind holes with the intermittent swirling gas jets. The entrance diameter is further reduced when the intermittent swirling gas jet is set to a higher pressure. The taper angle of the through holes as a function of the assist gas pressure is shown in Fig. 13. The figure also compares the results obtained with the continuous swirling gas jet and intermittent

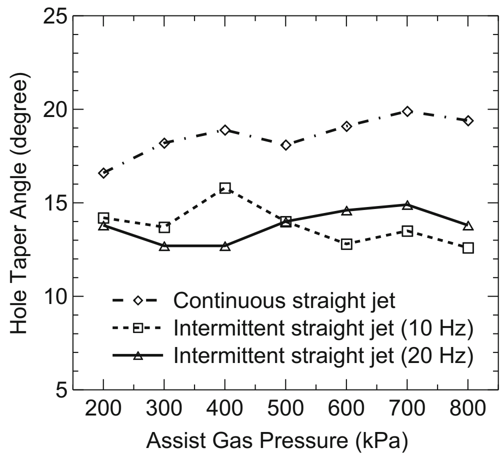

Fig. 9 Laser-drilled hole taper angle as a function of gas pressure for the cases of continuous swirling gas jet and 10- and 20-Hz intermittent swirling gas jets assisting

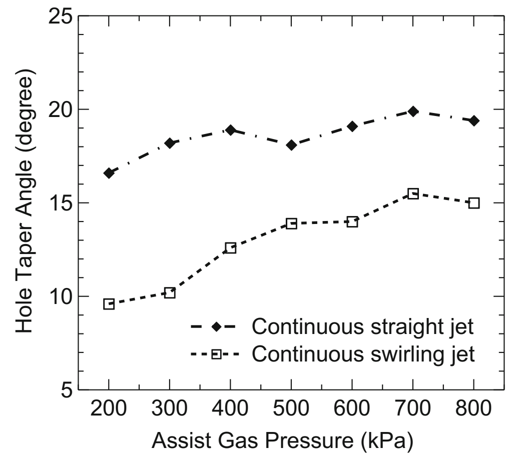

Fig. 11 Laser-drilled hole taper angle as a function of gas pressure for the cases of continuous straight gas jet and continuous swirling jets assisting

swirling gas jet with 10- and 20-Hz intermittent frequencies. At lower pressures, the taper angle is smaller with the continuous gas jet, while at higher pressures, the 20-Hz intermittent swirling gas jet produces the smaller hole taper angle.

It is worth noting that we calculated the taper angles using a simple formula, Eq. (12), rather than by fully examining the cross-sectional profiles for the through holes. Qualitatively speaking, the cross-sectional profiles of the through holes in the 500-μm workpieces would be similar to that shown in Fig. 3c with gas pressure equal to 500, 600, 700, and 800 kPa, where the holes are actually through in the 1000-μm workpiece. The walls of the blind holes would be curvy as the through holes. Consequently, the improved taper angle values shown in Figs. 9, 11, and 13 with the intermittent and/or swirling gas jets corresponds to a smaller entrance and/or a larger exit than that with a continuous straight gas jet of the same gas pressures, in which the reduction of the difference in hole entrance and exit diameters is achieved.

4 Conclusion

In conclusion, we have studied the effects of using intermittent gas jets to assist a fiber laser with a wavelength of 1090 nm when drilling SUS304 stainless-steel sheets. Compared with using continuous jet assistance, the utilization of the intermittent gas jets obviously improves the laser machining rate and drilling quality. With the proposed intermittent gas jet method, the cooling effect of a high-pressure continuous straight gas jet on CW laser drilling can be significantly reduced. As a result, the laser-drilled blind hole in a 1000-μm-thick SUS304 workpiece assisted by the intermittent straight gas jet under 40-s machining time can be about 1.7 times deeper than that by the continuous straight gas jet. We have discussed the effect of the frequency of the intermittent gas jets, modulating the intermittent frequency to improve the quality of the drilled through hole, i.e., the hole entrance/exit diameter and taper angle. Experimental results showed that improvement of reducing taper

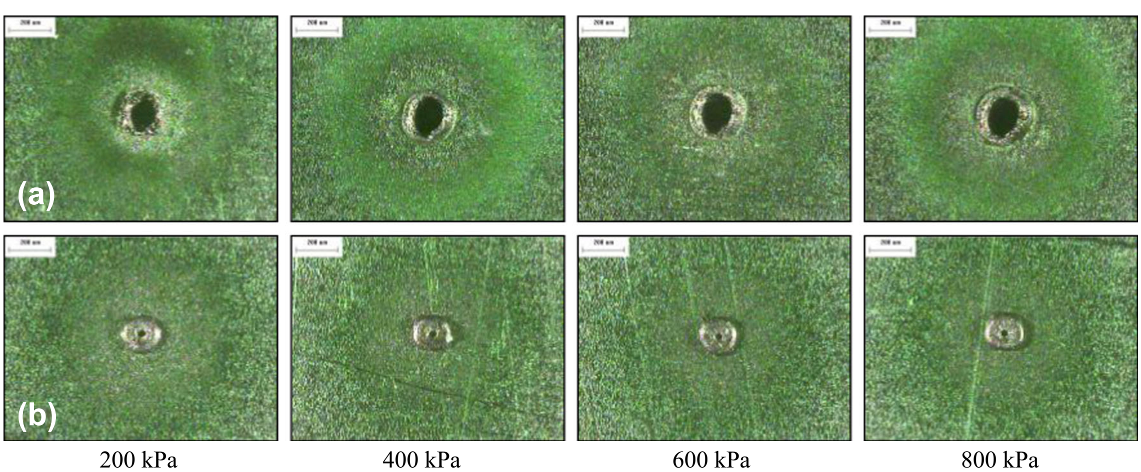

Fig. 10 **a** Entrance and **b** exit of laser-drilled holes assisted by the continuous swirling gas jet at different gas pressures

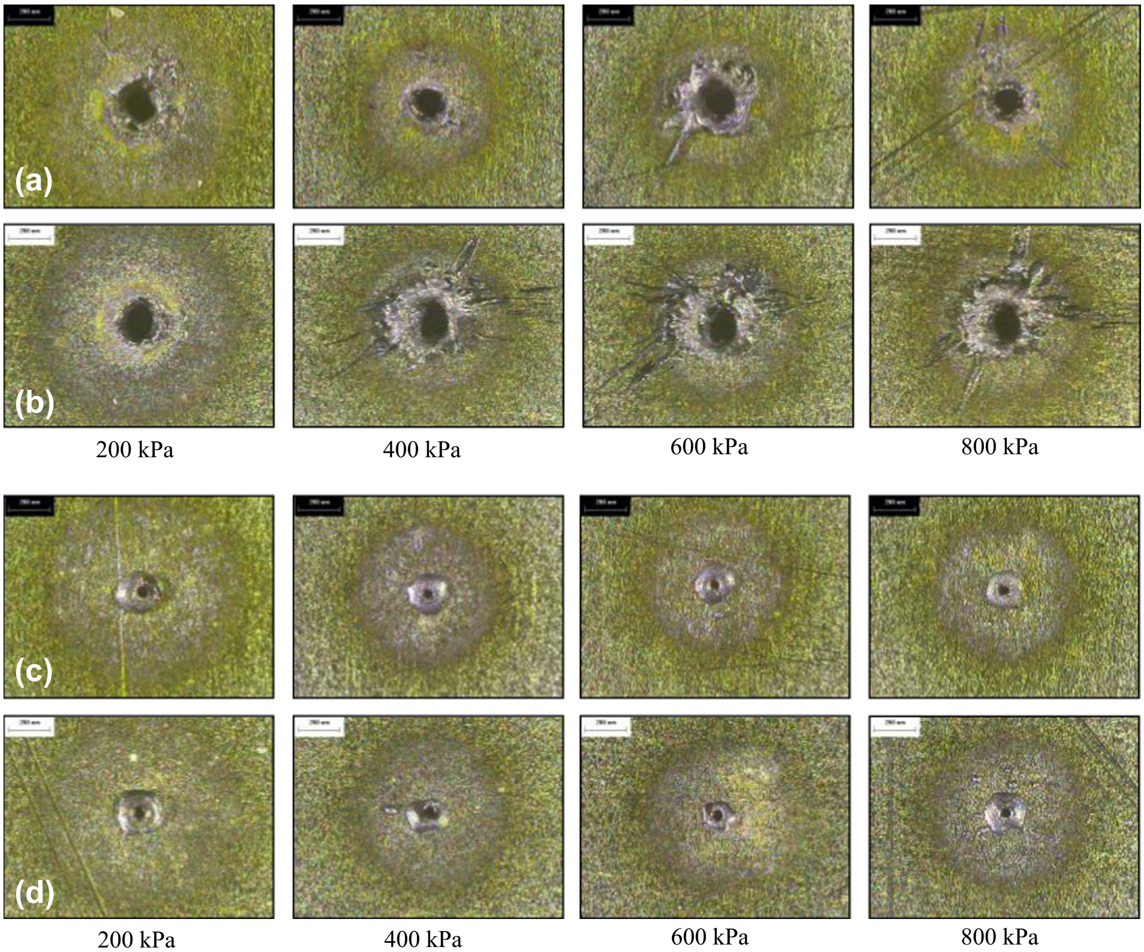

Fig. 12 **a** Entrance and **c** exit of laser-drilled through holes assisted by 10-Hz intermittent swirling gas jets of different and gas pressures. **b** Entrance and **d** exit of laser-drilled through holes assisted by 20-Hz intermittent swirling gas jets of different and gas pressures

angle from 20° to 14° can be achieved in a 500-μm-thick workpiece. Though using intermittent gas jets generally resulted in more spatter around the hole entrances, reducing the spatter around the hole by increasing the intermittent gas frequency and gas pressure was also demonstrated. We also proposed the use of continuous and intermittent swirling gas jets to assist CW laser drilling. Similar to laser drilling assisted by the intermittent straight gas jet, the laser drilling assisted by the intermittent swirling gas jet also improved the blind hole depth. Moreover, the swirling gas jets reduce spatter formation and the hole taper angle. Because the use of the continuous swirling gas jet reduces the pressure on the workpiece and thus suppresses the expansion of the hole entrance and reduces the backflow velocity at the hole exit, the amount of spatter around it decreases. Compared with straight gas jets, the swirling gas jets are advantageous in that they disperse the ejected molten material rather than ejecting material from inside the hole. According to the results of this study, increasing the intermittent gas frequency and pressure to further increase the machining rate by laser are expected.

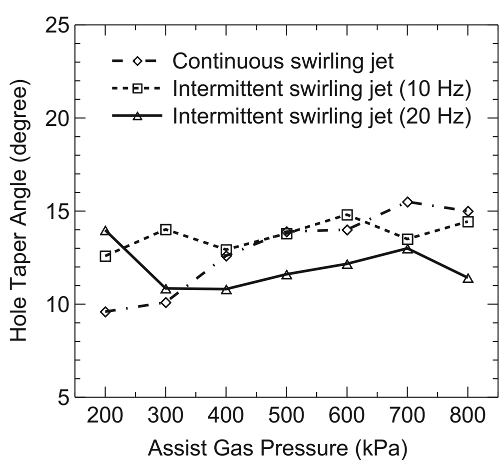

Fig. 13 Laser-drilled hole taper angle as a function of gas pressure for the cases of continuous swirling gas jet and intermittent swirling gas jets assisting

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