Ceramics International 43 (2017) 2938–2942

Contents lists available at ScienceDirect

Ceramics International

journal homepage: www.elsevier.com/locate/ceramint

Effect of laser scanning speed on geometrical features of Nd:YAG laser machined holes in thin silicon nitride substrate

Jinyang Zhang, Ying Long*, Shixian Liao, Hua-Tay Lin, Chengyong Wang

School of Electromechanical Engineering, Guangdong University of Technology, No 100 Waihuan Xi Road, Guangzhou Higher Education Mega Center, Panyu District, Guangzhou 510006, PR China

ARTICLE INFO

Keywords:
Laser machining
Si_3N_4 ceramic
Laser spot scanning speed

ABSTRACT

0.5 mm thick Silicon nitride (Si_3N_4) substrates with MgO-Y_2O_3 additives were employed for hole machining study with a Nd:YAG two-dimensional laser machining (cutting) system. The effects of laser scanning speed on features of the machined holes such as hole diameter, hole circularity, taper angle, heat affected zone (HAZ), recast layer, and micro-cracks were studied. The results show that the diameters at the front side are larger than the back side for all holes machined at different spot scanning speed. The taper angle of the machined holes decreases, while the hole circularity increases with the increase of the spot scanning speed. In addition, the heat-affected-zone (HAZ) was observed clearly around the back side of drilled holes, whose area decreases with the increase of the laser spot scanning speed. The result shows that the HAZ is the largest when the laser scanning speed is 20 mm/min. Nevertheless, the machined hole did not completely cross through the thickness of the substrate when the laser scanning speed was 60 mm/min. To obtain holes with relatively good quality, laser scanning speed should be controlled between 30 mm/min and 50 mm/min.

1. Introduction

Silicon nitride (Si_3N_4) ceramic has been considered as a potential material for power electronic substrates because of its good mechanical properties (strength and toughness) and high intrinsic thermal conductivity [1–3]. However, machining of silicon nitride ceramic is extremely difficult and time consuming owing to its high hardness. Laser machining, a non-contacting and abrasion-less technique, has been extensively used in the microelectronics industry due to its unique advantages such as no tool wear, no mechanical cutting force and vibration, high machining rate, and flexibility. Laser machining has been regarded as a potential machining method for a wide range of hard and brittle materials including ceramics such as alumina, silicon carbide, and silicon nitride [4,5].

For laser machining, high quality holes with desired characteristics is very important for application. The features of a high quality hole can be described as: taper angle, circularity, barreling, spatter formation, heat affected zone (HAZ), and so on [6,7]. However, a hole with perfect profile and very limited spattering is difficult to be fabricated because of the complicated laser machining process. It was reported that the laser machining process would be determined by the processing parameters for instance pulse repletion rate, pulse energy, interval of scanning lines, and so forth [8].

According to the kinematic of the front in the area of the workpiece where the material is removed, laser machining technique can be classified into three types: one-, two-, and three-dimensional machining [9]. Among them, one-dimensional laser machining is a process where the laser beam is fixed relative to the workpiece. In two-dimensional laser machining (cutting), the laser beam is in relative motion with respect to the workpiece. For three-dimensional machining, two or more laser beams are used and each beam forms a surface with relative motion to the workpiece.

So far, most of the researches have been focused on one-dimensional laser machining. However, the hole diameter machined by the one-dimensional laser machining technique is limited by the relative fixity between laser beam and workpiece. Holes with variable diameter can be machined by two-dimensional laser machining to meet different applications. It is also possible to machine hole with different geometric shapes by controlling the cutting path of the laser beam. During these years, many researchers have been reported on one-dimensional laser machining process for alumina electronic substrates and the effects of processing parameters on pore quality. However, only a limited number of studies describing laser machining of Si_3N_4 based ceramics have been reported up to date [10–15].

In the process of two-dimensional laser machining, one of the most important parameters that affects the hole quality is the laser spot

---

* Corresponding author.
E-mail address: longying0306@163.com (Y. Long).

http://dx.doi.org/10.1016/j.ceramint.2016.10.199
Received 1 October 2016; Received in revised form 16 October 2016; Accepted 31 October 2016

Table 1
Chemical composition and property parameters of Si_3N_4 substrates.

Chemical composition	90 wt%α-Si_3N_4, 8 wt%Y_2O_3, 2 wt%MgO
Density (g/cm^3)	3.24
Thermal conductivity (W/mK)	46
Hardness (HV)	1837.7 ± 79.5
Fracture toughness (MPa $m^{1/2}$)	8.39 ± 0.38
Bending strength (MPa)	1113 ± 92

scanning speed. Any change in the laser spot scanning speed would directly determine the energy or heat transferred to the material, which therefore influences the quality of the machined holes to various degrees. The objective of this study is to machine the Si_3N_4 ceramic substrates using two-dimensional laser machining technique by changing the laser spot scanning speed. The effect of laser scanning speed on hole quality was investigated and reported. To our knowledge, no relative reports have been published yet.

2. Experimental procedure

0.5 mm thick Si_3N_4 ceramic substrates were employed for two-dimensional laser machining by using a Nd: YAG laser machine. The Si_3N_4 substrates were produced by using a hot pressing (HP) furnace (Weitai Technology, Shenyang, China) at a temperature of 1800 °C with 20 MPa pressure for 120 min under the protection of flowing N_2. The chemical composition and some typical physical properties of the Si_3N_4 substrate are listed in Table 1. The wavelength of the laser is 1064 nm with a pulse repetition frequency (PRF) of 0.5–50 kHz. The average power of the laser is 200 W, with a 380 V three-phase alternating input voltage and a working frequency of 50 Hz. The working current is in the range of 10–30 A. The pulse duration is in the 20 ms range. The spot size of the laser beam is 0.15 mm. The maximum laser spot scanning speed of the laser machine is 150 mm/min. In in the present work, speed ranging from 20 to 60 mm/min with an interval of 10 mm/min was applied for hole machining. Four holes were machined under each laser spot scanning speed. The major and minor diameters of the front side and back side of each hole were measured as the average value of the four holes. The average value of four major diameters is regarded as the major diameter (D_{max}) under each laser spot scanning speed, while the minor diameter (D_{min}) is obtained by the same method. The front or back side hole diameters (D_{en} or D_{ex}) is the average value of D_{max} and D_{min}. The hole diameters were measured by an optical microscope with 0.2 µm resolution (optical microscope MIT300, AOTE, China). The measurement of each diameter value were repeated for at least three time to avoid the measurement uncertainty as much as possible. The morphology and quality of the laser-machined holes were characterized using scanning electron microscope (SEM, Nova NanoSEM430, FEI, USA). Element analysis of the melt around the front side of the holes was carried out using an energy dispersive spectrometer (EDS) attachment available with the SEM.

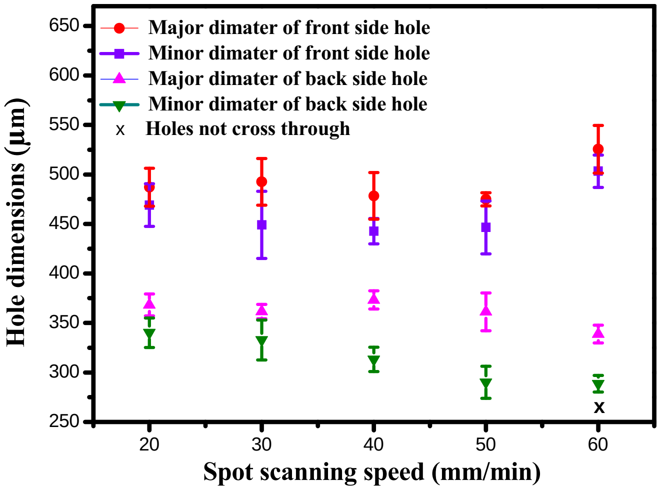


Fig. 2. Effect of laser spot scanning speed on the hole dimensions of the front and back side of the holes.

3. Results and discussion

Typical SEM images taken from the front side, back side, and cross-section the holes machined under various laser spot scanning speeds

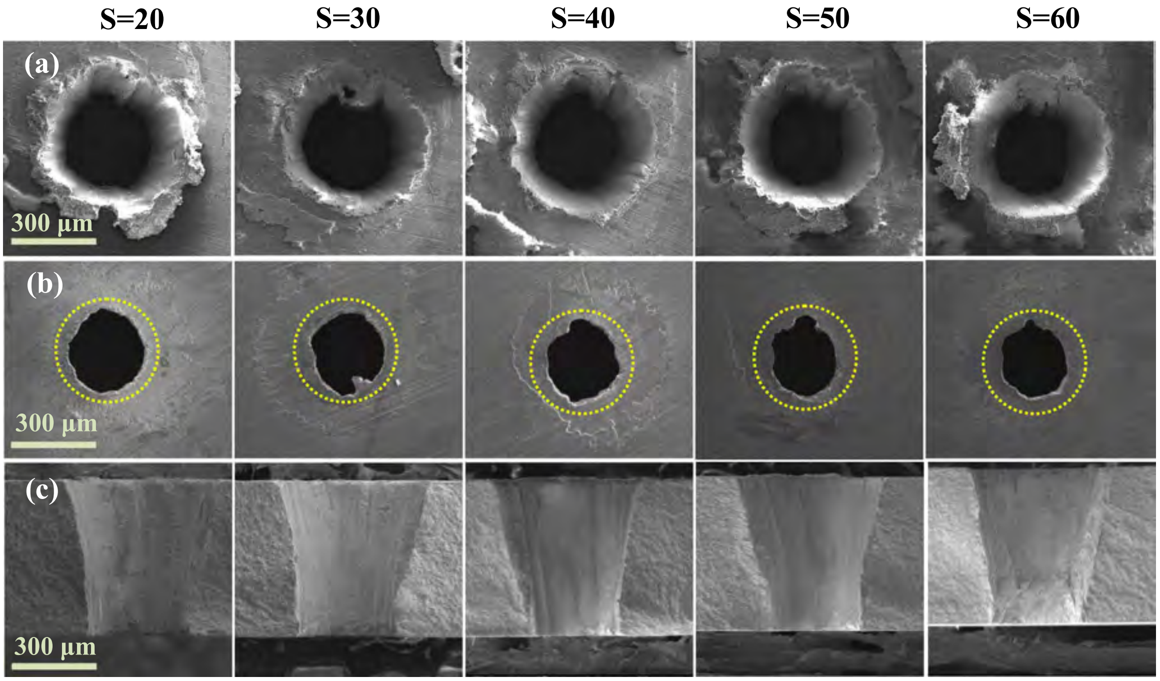


Fig. 1. SEM images taken from the (a) front side, (b) back side and (c) cross-section of holes laser machined at 20, 30, 40, 50, 60 mm/min, respectively.

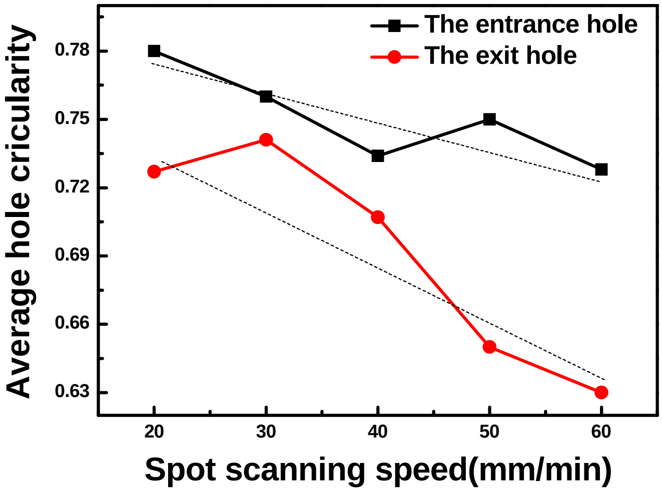


Fig. 3. Variation of the average hole circularity as a function of laser spot scanning speed.

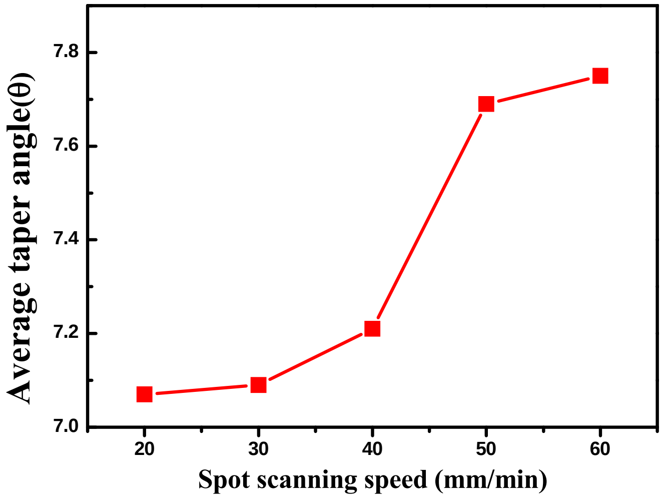


Fig. 4. Variation of the average taper angles as a function of laser spot scanning speed.

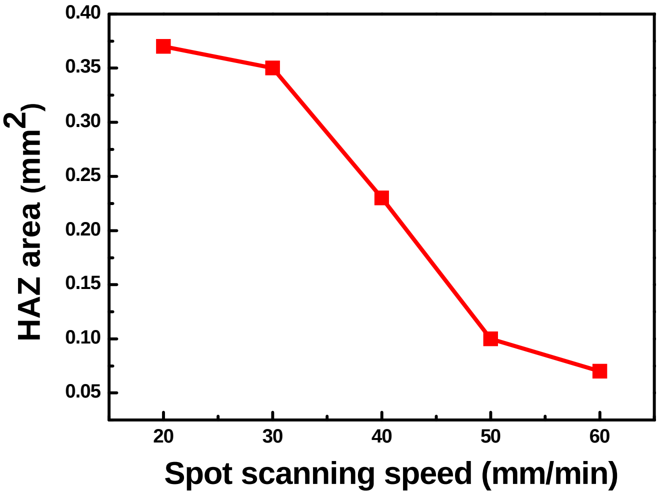
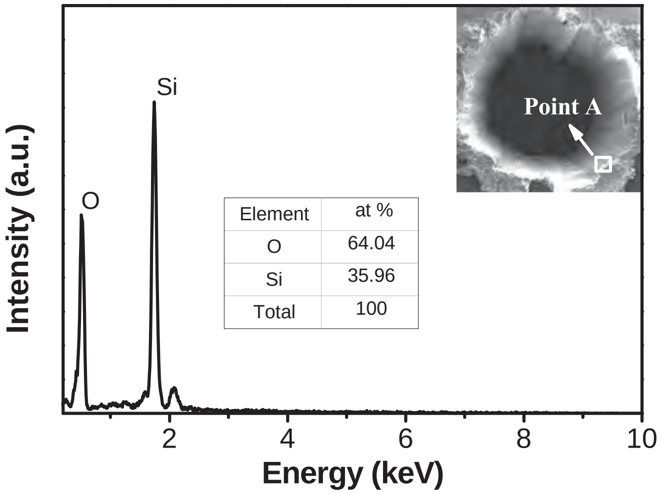


Fig. 5. Influence of laser scanning speed on HAZ.



Element	at %
O	64.04
Si	35.96
Total	100

Fig. 6. Element analysis results by EDS from point A at front side of the hole.

are shown in Fig. 1. It can be seen that the average diameter of the hole at the front side is in the range of 425–550 µm while the average diameter of the hole at back side is in the range of 225–400 µm. In general, for all groups of holes machined under different spot scanning speeds, the average hole diameters at the front side are obviously larger than those of the back side. Fig. 1(c) show pictures taken from the cross-section of typical machined holes under each laser spot scanning speed, from which it can be observed that all machined holes are shaped like a cone. In addition, compared with the front side of the holes, the shape of the back side is relatively more irregular with lower circularity degree (see Fig. 1) Fig. 1. Furthermore, irregular and incomplete melt is found around the front side of holes (see Fig. 1(a)). For the hole machined at laser spot scanning speed of 30 mm/min, the melt area outside the hole is the biggest. On the other hand, heat-affected zone (HAZ) can be observed obviously around the back side of the machined holes (Fig. 1(b)).

The hole diameters variation of the front and back side as a function of the laser spot scanning speed is shown in Fig. 2. Results show that there is a big difference between hole diameters in the front and back side, which is is about 120–130 µm. The average diameters of the front side of all machined holes are similar within the measurement uncertainties. On the other hand, the average diameter of back side holes decreases with the increasing of laser spot scanning speed. It is worth to note that, when the laser spot speed is up to 60 mm/min, two of the four holes were not cross through the thickness of the substrates, which is also shown in Fig. 2.

Fig. 3 shows that the variation of the average hole circularity as a function of the laser spot scanning speed for the holes. The circularity degree (C) of a hole is calculated by

$$C = D_{\min}/D_{\max} \tag{1}$$

Cylindricality degree of a hole is given by taper angle [16]. Taper angleθ can be calculated by the following formula,

$$\theta = tg^{-1}[(D_{en} - D_{ex})/2t] \tag{2}$$

where D_{en} and D_{ex} are front and back side hole diameters respectively; t is the thickness of the material.

Fig. 3 shows the variation of the average hole circularity as a function of laser spot scanning speed. It can be found that both the average circularity of the front and back side of the holes decrease with the increasing laser spot scanning speed. However, the effects of laser spot scanning speed on circularity of the holes on the back side are greater than that holes on the front side. This is because when the laser spot scanning speed increases, the processing time on the hole decreases correspondingly, which results in the reduction of the total input heat energy. Moreover, the input heat energy decreased gradually with the continue of the laser machining process. The higher the spot scanning speed, the faster the decreasing of the input heat energy. Therefore, the circularity of the holes on the back side decreased faster with the increasing spot scanning speed.

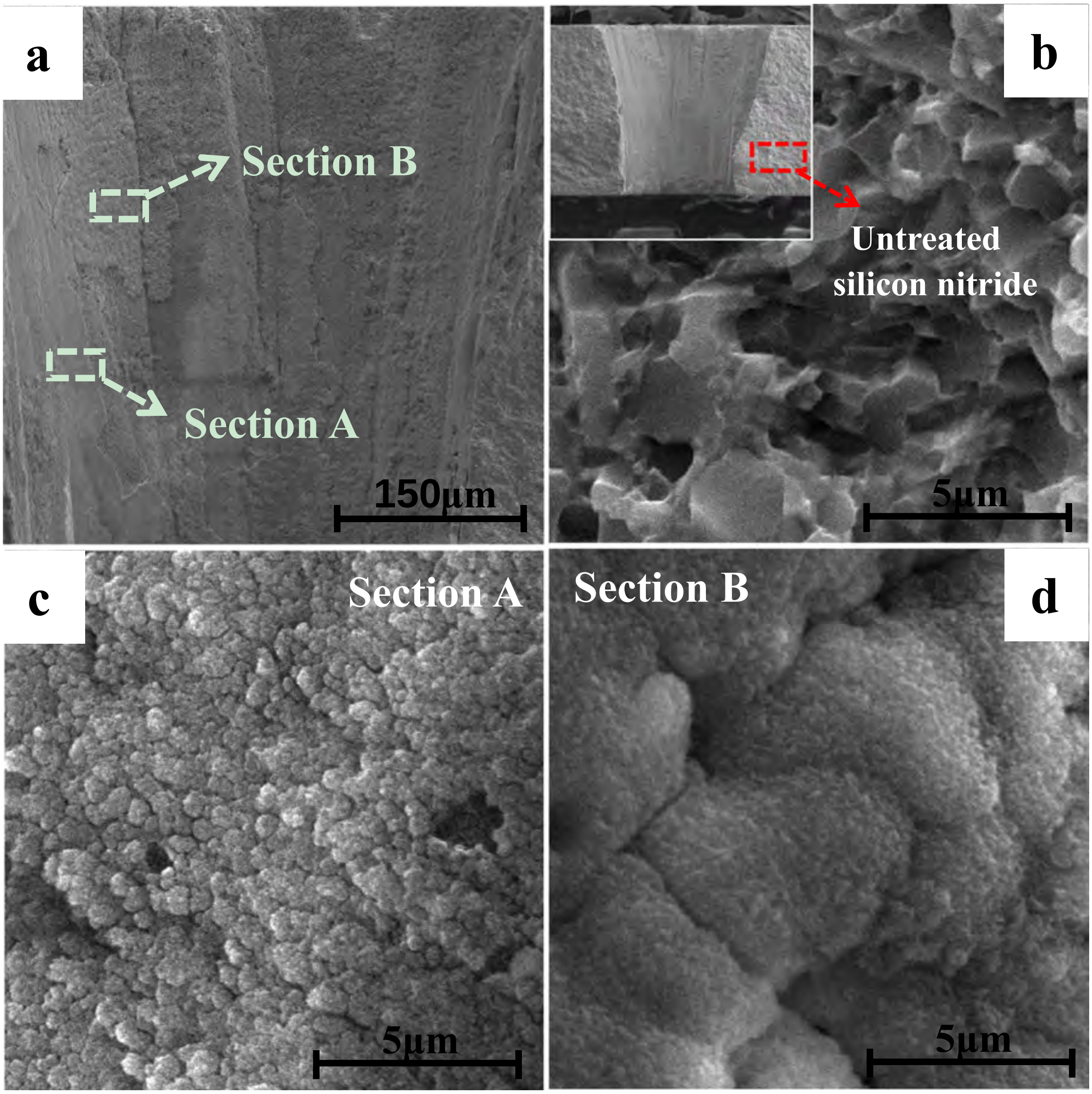


Fig. 7. SEM images taken from the cross-section of a typical machined hole: (a) low magnification image; (b) untreated silicon nitride; (c) thin and smooth recast layer; (d) rough recast layer.

Fig. 4 shows the variation of the average taper angles as a function of the laser spot scanning speed. It was shown that the average taper angles increase with the increasing laser spot scanning speed. Since the holes diameter on the front side does not vary greatly, the average taper angles increases with the laser spot scanning speed. When the spot scanning speed increases to 60 mm/min, it is possible that the input energy is not high enough to remove the substrate materials at the end of the machining process. This can explain why two holes were not completely cross through the thickness of the substrates when the laser spot scanning speed is 60 mm/min.

As shown in Fig. 1(b), the heat-affected zone (HAZ) is apparently observed around the holes on the surface of back side of the silicon nitride substrate. To study the effect of the laser scanning speed on HAZ, the change of HAZ area in the function of the scanning speed is shown in Fig. 5. It can be found that the HAZ decreases sharply with the increase of the laser spot scanning speed. As mentioned early, the total heat energy for machining holes decreases with the increase of laser scanning speed. As a result, the energy transferred to the back side of the holes decreases, which leads to the decrease of the HAZ area. Therefore, to obtain a hole with relatively small HAZ area, a relatively high laser spot scanning speed should be used during machining process.

In Fig. 1, it can be also found that irregular and incomplete melt around the holes on the front side. The chemical composition of the melt around the machined holes on the front side can be identified as silicon dioxide as can be seen from the EDS result (Fig. 6). When Si_3N_4 was machined by laser in air, SiO vapor was formed easily by an oxidation decomposition of Si_3N_4. In addition, SiO vapor was oxidized immediately and changed to solid phase SiO_2 [18]. These reactions can be expressed as follows,

$$2Si_3N_4\ (s) + 3O_2\ (g) \rightarrow 6SiO(g) + 4N_2(g) \tag{3}$$

$$2SiO\ (g) + O_2\ (g) \rightarrow 2SiO_2\ (s) \tag{4}$$

$$Si_3N_4\ (s) + 11/2O_2\ (g) \rightarrow 3SiO\ (g) + 4NO_2\ (g) \tag{5}$$

Based on above chemical reactions, a silicon dioxide-rich melt from oxidation of Si_3N_4 forms during the laser spot machining. The melt will be pushed up and out of the hole by the high vapor pressure, which may produce re-solidified material, affect the hole shape, or even partially block the holes during the laser machining processs [17].

The morphologies of the cross-section of a typical machined hole

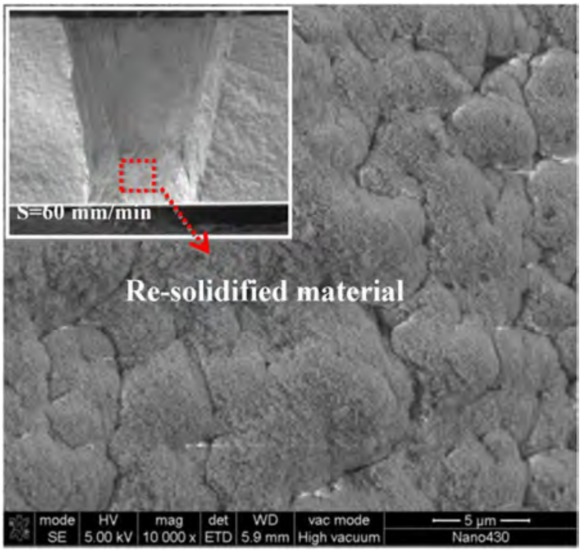


Fig. 8. High magnification SEM image taken from the bottom of the machined hole at the laser spot scanning speed of 60 mm/min.

are shown in Fig. 7. The cross-section of the hole can be divided into two areas, one is a thin and smooth recast layer(see Fig. 7(c)), with grain size of less than 1 μm. The other is a rough recast layer (see Fig. 7(d)), with grain size of about 4–6 μm. For comparsion, the morphology of the cross-section of the untreated silicon nitride material is , shown in Fig. 7(b). During the hole machining process, a thin molten layer is first formed with the absorption of laser energy. When the motlen material reaches the vaporization temperature, the material vapor evaporates from the surface and the melt is pushed out. As part of this molten material resolidifies on the hole wall during the laser machining process, a recast layer is therefore formed. This can also explain the presence of spattering observed around the hole on the front side of the holes, as shown in Fig. 1(a). The possible reasons for the formation of these two recast layers with different structures can be explained as follows. When Si_3N_4 susbstrate was machined in air, an oxide layer of SiO_2 was readily formed on the inner wall of the holes. For the external layer which has sufficient O_2, a rough SiO_2 layer with large grains forms, as can be seen in Fig. 7(d). On the other hand, the grain growth of SiO_2 in the internal layer is restrained because the supply of O_2 is insufficient. Therefore, a thin and smooth layer is fomed (Fig. 7(c)). In addition, the external SiO_2 layer at the wall of the holes is easy to peeling off. This may be attributed to the weak interface adhesion between the resolidified material and the wall of the holes owing to the thermal stress formed during the laser machining process [19]. It is worth to note that, the formation of the melt will affect the thermal conductivity of the silicon nitride substrates since SiO_2 has lower thermal conductivity than that of the Si_3N_4. In addition, no micro-cracks were formed on the wall of machined hole.

In addition, there is a large amount of re-solidified material observed at the bottom of the hole when laser spot scanning speed increased to 60 mm/min, as can be seen in Fig. 8. This is because with such a high spot scanning speed, the heat energy is not high enough to complete the melting and vaporization process of the machined material. As a result, material in semi-molten state can not be carried out by vapor in time and finally re-solidified at the bottom of hole, which may even lead to the non-completed cross through the thickness of the machined substrate. From this point of view, the laser scanning speed should be less than 60 mm/min to obtain holes with relatively good quality.

4. Conclusions

In this paper, 0.5 mm thickness Si_3N_4-based substrate sintered with $MgO-Y_2O_3$ oxides was employed for laser hole machining using Nd:YAG laser machine. The effect of the laser spot scanning speed on the dimensions, average hole circularity, average taper angles, HAZ area, recast layer were studied. The results show that the hole diameters at the front side are larger than those at the back side. The taper angle of the holes increases and the hole circularity decreases with the laser spot scanning speed. Molten materials were clearly observed around the front side of the drilled holes, while HAZ is observed on the back side of the machined holes. As the HAZ presents a linear decrease trend with the increase of the laser scanning speed, holes machined at the laser scanning speed of 20 mm/min exhibit the largest HAZ. On the other hand, two of the four holes machined at the laser scanning speed of 60 mm/min are not completely cross through the thickness of the substrates. Therefore, the laser scanning speed should be controlled from 30 mm/min to 50 mm/min to machine holes with relatively good quality.

Acknowledgment

This work was financially supported by 1) the Project of Innovative and Entrepreneurial Research Team Introduction Program of Guangdong Province (No. 2013G061); 2) Guangdong Natural Science Foundation (No. 2014A030310182); 3) Guangdong Natural Science Foundation (Nos. 2015A030313491).

References

[1] A. Kelly, N.H. Macmillan, in strong Solids (Monographs on the Physics and Chemistry of Materials), Oxford University Press, New York, 1986.
[2] J.B. Wachtman, Mechanical Properties of Ceramics, John Wiley & Sons, New York, 1996.
[3] A.J. Pyzik, D.F. Carroll, Technology of self-reinforced silicon nitride [J], Annu Rev. Mater. Sci. 24 (1994) 189–214.
[4] A.S. Kuar, B. Doloi, B. Bhattacharyya, Modelling and analysis of pulsed Nd:YAG laser machining characteristics during micro-drilling of zirconia (ZrO_2), Int. J. Mach. Tools Manuf. 46 (2006) 1301–1310.
[5] C. Bagger, F.O. Olsen, Pulsed mode laser cutting of sheets for tailored blanks, J. Mater. Process. Technol. 115 (2001) 131–135.
[6] N. Masmiati, P.K. Philip, Investigations on laser percussion drilling of some thermoplastic polymers, J. Mater. Process. Technol. 185 (2007) 198–203.
[7] M. Ghoreishi, Statistical analysis of repeatability in laser percussion drilling, Int. J. Adv. Manuf. Technol. 29 (2006) 70–78.
[8] C. Wang, X. Zeng, Study of laser carving three-dimensional structures on ceramics: quality controlling and mechanisms, Opt. Laser Technol. 39 (2007) 1400–1405.
[9] A.N. Samant, N.B. Dahotre, Laser machining of structural ceramics-a review, J. Eur. Ceram. Soc. 29 (2009) 963–993.
[10] L. Hong, L. Li, C. Ju, Investigation of cutting of engineering ceramics with Q-switched pulse CO_2 laser, Opt. Lasers Eng. 38 (2002) 279–289.
[11] L. Hong, L. Li, A study of laser cutting engineering ceramics, Opt. Laser Technol. 31 (1999) 531–538.
[12] A.N. Samant, N.B. Dahotre, Absorptivity transition in the 1.06 μm wavelength laser machining of structural ceramics, Int. J. Appl. Ceram. Technol. 8 (2011) 127–139.
[13] A.N. Samant, N.B. Dahotre, Three-dimensional laser machining of structural ceramics, J. Manuf. Process. 12 (2010) 1–7.
[14] A.N. Samant, N.B. Dahotre, Differences in physical phenomena governing laser machining of structural ceramics, Ceram. Int. 35 (2009) 2093–2097.
[15] A.N. Samant, N.B. Dahotre, Physical effects of multipass two-dimensional laser machining of structural ceramics, Adv. Eng. Mater. 11 (2009) 579–585.
[16] S. Bandyopadhyay, J.K. Sarin Sundar, G. Sundararajan, S.V. Joshi, Geometrical features and metallurgical characteristicsof Nd:YAG laser drilled holes in thick NI718 and Ti-6Al-4V sheets, J. Mater. Process. Technol. 127 (2002) 83–95.
[17] L. Tunnaa, W. O'Neilla, A. Khana, C. Sutcliffe, Analysis of laser micro drilled holes through aluminium for micro-manufacturing applications, Opt. Lasers Eng. 43 (2005) 937–950.
[18] I. Shigematsu, K. Kanayama, A. Tsuge, Analysis of constituents generated with laser machining of Si_3N_4 and SiC, J. Mater. Sci. Lett. 17 (1998) 737–739.
[19] M.M. Hanon, E. Akman, B. Genc Oztoprak, Experimental and theoretical investigation of the drilling of alumina ceramic using Nd:YAG pulsed laser, Opt. Laser Technol. 44 (2012) 913–922.