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ScienceDirect
Trans. Nonferrous Met. Soc. China 22(2012) s801−s807
Transactions of Nonferrous Metals Society of China
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# Surface effects of hybrid vibration-assisted femtosecond laser system for micro-hole drilling of copper substrate

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Received 21 May 2012; accepted 1 November 2012

**Abstract:** The ultrafast laser based hybrid machining system was studied and a novel approach was demonstrated to improve laser machining quality on metals by vibrating the optical objective lens with a low frequency (500 Hz) and various displacements (0−16.5 μm) during a femtosecond laser machining process. The laser used in this experiment is an amplified Ti:sapphire femtosecond ($10^{-15}$ s) laser system that generates 100 femtosecond pulses having an energy of 3.5 mJ/pulse with a 5 kHz repetition rate at a central wavelength of 790 nm. It is found that both the wall surface finish of the machined structures and the aspect ratio obtained using the frequency vibration assisted laser machining are improved compared with those derived via laser machining without vibration assistance.

**Key words:** femtosecond laser; hybrid machining; vibration-assisted machining; surface roughness; aspect ratio

## 1 Introduction

Laser machining technologies using ultrashort pulse lasers are extensively used for manufacturing small-scale and microcomponents in modern manufacturing industries. Material processing using a femtosecond laser has recently attracted strong interest as it can be employed to achieve high quality, damage-free processing [1,2]. Femtosecond lasers are increasingly used for micro- and sub-micro machining applications, as they provide an improved machining quality and increase the machining capacity compared with other lasers [3]. The main features of femtosecond-pulse laser ablation are the existence of a sharp fluence threshold for material removal that is much lower than that for longer laser pulses, rapid energy deposition and fast ablation without heat- and shock-affected zones, and the possibility of controllable ablation and production of high-quality structures in any solid material [4,5].

However, one of the major drawbacks of femtosecond laser machining is that the side wall of the machined surface and the adjacent machined areas are usually covered with re-solidified and re-deposited material particles as a result of high energy laser beam interactions with the substrate material. Nanostructures like nano-sized droplets and nano-joining have also been generated through plume deposition of femtosecond pulsed laser ablated material [6,7].

Nano-joining must be further developed in order to build and assemble functional nano-devices with dissimilar nano- and/or molecular components. In addition, nano-joining allows the integration of micro- and nano-devices with micro-and macrosystems and surroundings. Welding and joining is an essential step in the fabrication of various devices at different scales including macro-, micro- and nano-scale.

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**Foundation item:** Project (2010-0008-277) supported by NCRC (National Core Research Center) Program through the National Research Foundation of Korea Funded by the Ministry of Education, Science and Technology
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DOI: 10.1016/S1003-6326(12)61807-X

devices at different scales including macro-, micro- and nano-scale. As devices become increasingly smaller, challenges faced in micro and nano-joining must be overcome before these joints can be safely implemented. In particular, it is necessary to determine how to robustly join these miniature building blocks while avoiding excessive damage. When the building blocks are reduced to a submicron scale or even to a range of nanometers, such as in the fabrication of nanomechanical engineering systems (NEMS), melting has to be controlled within a thickness of a few nanometers. Ultrafast pulsed laser is an innovative tool used in this field for nanoscopic processing. Femtosecond laser irradiation can result in ultrafast and non-thermal melting of solid materials, thus showing promise for developing novel joining technologies for nano- and/or molecular devices. With the development of nanoscience and technology, nanoscopic joining technologies are gaining more significance [8,9].

In this work, an ultrafast laser was developed based hybrid machining system and demonstrate a novel approach to improve laser machining quality by vibrating the optical objective lens with a low frequency (500 Hz), and controlled the aspect ratio of machined materials by applying various displacements (0−16.5 μm) of the vibrator during the laser machining process. It is found that both the wall surface finish of the fabricated microholes and the aspect ratio using the low frequency vibration assisted laser drilling are improved, compared with the results obtained with laser machining without vibration assistance. This is the report on the use of vibration in the femtosecond laser drilling process, which reduced the re-solidified and re-casted particles on the wall surfaces, thereby providing fine side wall surface and a means of controlling the machined depth. Vibration has also been superposed on the normal objective lens movement to increase the blowing effect during the femtosecond laser machining process. A systematic study of the effects of vibration on the femtosecond laser machining performance for fabricating microholes in metal has been still uncompleted. This is report on experiments applying low frequency vibration to the femtosecond laser machining process to attain significantly improved surface roughness of the machined side wall and increased machined depth.

## 2 Experimental

A schematic diagram of the experimental setup for vibration assisted femtosecond laser machining is shown in Fig.1 The irradiation laser used in the experiment was a Ti: sapphire oscillator amplifier laser system based on the chirped pulse amplification technique with a 100 femtosecond pulse duration, 3.5 W maximum output power, and 1 kHz repetition rate at a central wavelength of 795 nm. The vibration assisted femtosecond laser machining system consists of vibrator, a PZT amplifier, function generator, and oscilloscope. The amplitude and frequency of the vibrator (Model No. PI P−725.CDD) were calibrated using an oscilloscope. To introduce

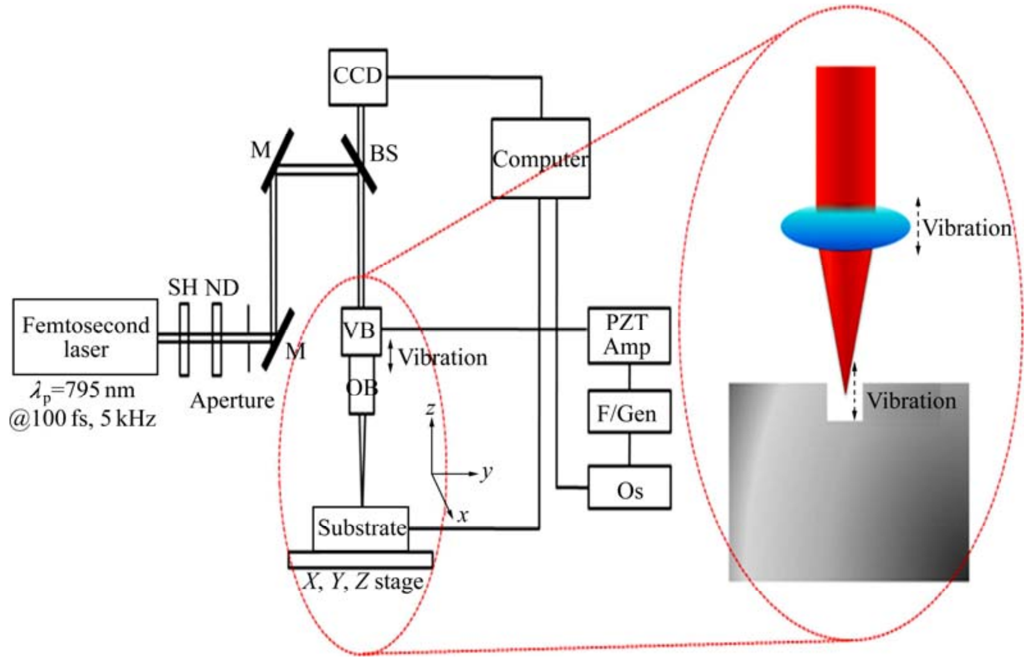


**Fig. 1** Schematic diagram of experimental set-up of vibration-assisted femtosecond laser hybrid machining system (SH—Shutter; ND—Neutral density filter; M—Mirror; CCD—CCD camera; BS—Beam splitter; OB—Objective lens; VB—Vibrator; PZT Amp—PZT Amplifier; F/Gen—Function generator; OS—Oscilloscope)

vibration to the femtosecond laser machining, a vibrator was installed on the objective lens. Cu samples were prepared by mechanically polishing the surfaces. Copper has been selected as the work material because it is an excellent electrical material and is employed in numerous applications in electric-engineering and micro-systems devices. A linearly polarized laser beam with a Gaussian profile was focused tightly onto a commercially available Cu substrate through an objective lens (N.A.: 0.26) with various frequencies. The Cu substrate was set on the *X*−*Y*−*Z* stage to be scanned, with a space resolution of 50 nm. The energy of the incident beam irradiating the Cu substrate was controlled using neutral density (ND) filters inserted between the laser and the focusing objective lens. The machined structures were observed from a direction perpendicular to the optical axis using an optical microscope with a CCD camera connected to a computer. To produce nanostructures, a linearly polarized femtosecond laser beam was weakly focused onto the sample surface at the normal incident. A train of laser pulses was used to irradiate the sample and the number of the pulses was controlled by an electromechanical shutter. Experiments were conducted under the same laser conditions (pulse energy and time duration) with and without vibration assistance for comparison. The examination of the entrance and the wall surface morphology of the processed samples were studied with a scanning electron microscope (SEM) in order to observe burrs and the formed nano-structures (re-solidified particles). The line machined samples by femtosecond laser machining with and without vibration assistance were vertically polished at fine step to reveal the depth of the machined structure and were studied with a scanning electron microscope (SEM).

## 3 Results and discussion

First, we studied the evolution of structural formation following 25000 pulses irradiation on the Cu substrate at 50 μJ pulse energy during 5 s to confirm the effect of vibration assistance. In this experiment, a Ti: Sapphire femtosecond laser delivering 50 μJ pulses with a 5 kHz repetition rate and a pulse width of 100 femtosecond was irradiated. Energy focused into the sample was varied using a combination of neutral density filters. We used three-dimensional stages to move the Cu substrate in the *x*-, *y*- and *z*- directions and a 10 × (NA: 0.26) microscopic objective lens to focus the laser onto the Cu substrate. The vibrator was periodically moved in the vertical direction with a frequency and displacement height of 500 Hz and 800 nm, respectively. Figures 2(a) and (b) show SEM images of the hole at the entrance end drilled by focused laser beams on the surface of the Cu substrate without vibration assistance and with vibration assistance, respectively. The hole structures were a result of 25000 overlapping pulses at energy of 50 μJ/pulse without and with vibration of the objective lens. The diameter of the machined hole was 50 μm. Femtosecond laser machining with vibration assistance improved the removal of burr and debris at the machined entrance in comparison with femtosecond laser machining without vibration assistance as shown in Fig. 2. From these results, the femtosecond laser machining assisted vibration with frequency shows a blowing effect similar to the case of using high-pressure gas through a nozzle.

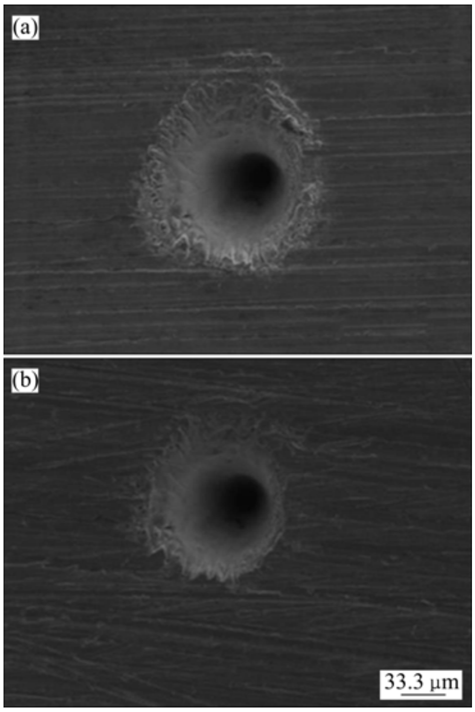


**Fig. 2** SEM images of hole at entrance end drilled without vibration assistance (a) and with vibration assistance (b)

Following femtosecond pulse irradiation, some nanostructures were formed around the side wall region of the machined hole. Figure 3 shows the side wall surfaces of hole structures obtained with 25000 overlapping pulses at energy of 50 μJ/pulse without and with vibration of the objective lens. Figures 3(a)−(d) show SEM images of the side-wall surface of a Cu substrate generated by femtosecond laser machining without vibration assistance and with vibration assistance, respectively. It can be seen that several types of nano-joining and nanostructures uniformly form on the metal surface by femtosecond laser machining without vibration assistance, as shown in Figs. 3(a)−(d). Nanostructures are formed on the side wall surface, mostly with size up to 700 nm in diameter. Without

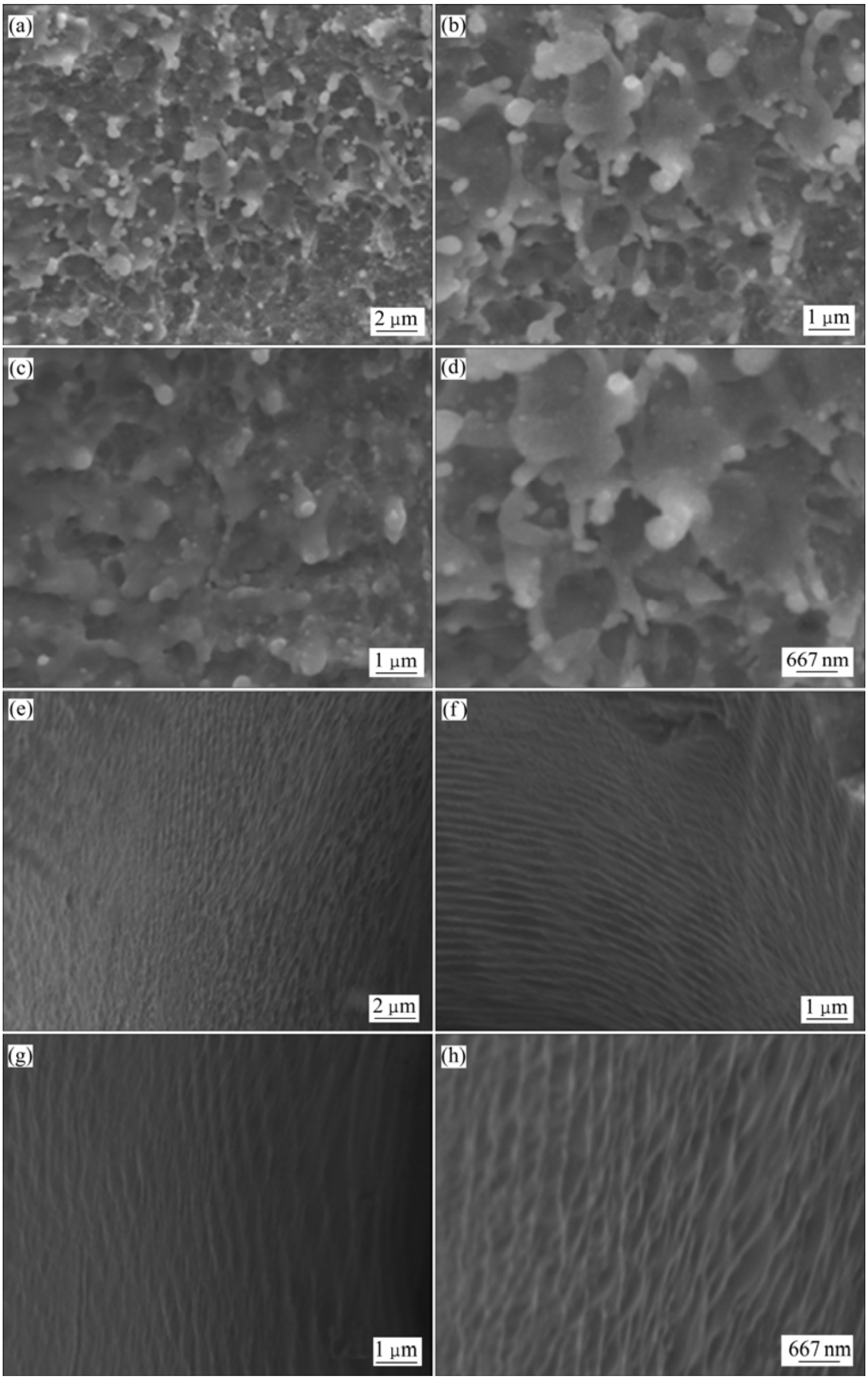


**Fig. 3** SEM images of side-wall surface generated by femtosecond laser drilling of copper substrate (Frequency and displacement of vibration are 500 Hz and 800 nm, and the irradiated energy is 50 μJ/pulse.): (a−d) Without vibration assistance; (e−h) With vibration assistance

vibration assistance, the wall surface shows a high degree of nano-joining and is largely covered with nano-droplets. In contrast, in the case of vibration-assisted femtosecond laser machining, as shown in Figs. 3(e)−(f), the wall surface appears much cleaner with the absence of the nano-joining and nano-droplet structures. This is attributed to a stirring effect stemming from vibration of the objective lens (or focused beam point), which enhances the heat transfer of the ablated particles. The increased cooling help to reduce the probability of particles being joined to the wall surfaces, as in a previously reported case of high frequency ultrasonic vibration of a substrate [10].

Several vibration displacements were used under the same conditions of femtosecond laser irradiation, with the aim of obtaining control over the aspect ratio. The depth data were obtained by polishing the substrate surface step by step and then measured with a SEM. Figure 4 shows cross-sectional SEM images of a Cu substrate machined with vibrations of various displacements using a femtosecond laser with a pulse energy of 50 μJ/pulse and a scanning speed of 0.01 mm/s. In a caption of Fig. 4, *D* is the displacement of vibration of the objective lens at 500 Hz frequency during the femtosecond laser machining process. The motion of the vibrator is such that it periodically moves in the vertical direction with a frequency (of 500 Hz) and displacement height of 0, 3.45, 16.2, and 15.75 μm, respectively. The frequency is the same as that of the vibrator used in this experiment. Figure 4(a) shows a cross-sectional SEM image of a grooved structure formed without vibration assistance by femtosecond laser machining. Note that the entrance diameter of the vibration-assist laser machining is slightly larger and less regular due to vibration of the substrate during laser machining, as shown in Figs. 4(b), (c) and (d). The calculated aspect ratios are 1.26, 1.54, 1.90, and 1.94, respectively, based on the entrance diameter. With vibration, the machined depth is increased while the displacement of vibration increases in comparison with depth obtained without vibration. A significant increase in the machined length was obtained using vibration of the objective lens according to the vibration displacement. With the introduction of vibration, heat transfer is more efficient due to local force convection. As a result, the ablated particles cool faster and has less tendency to agglomerate. A less dense plasma cloud was expected to form, thus increasing the efficiency of the laser machining as the laser beam has greater likelihood of hitting the substrate surface. The aspect ratio is consequently higher with the vibration-assisted laser machining. The use of vibration improves the debris removal and increases the machined depth.

Figure 5 shows the results obtained in this experiment. An illustration of the depth of holes and SEM images of the wall surface in a Cu substrate with and without vibration of objective lens by femtosecond laser irradiation are shown in Figs. 5(a) and (b), respectively, where *h* is the depth of the machined structure without vibration of the objective lens during the femtosecond laser machining process, *α* is the increased machining distance due to the vibration of objective lens during femtosecond laser machining process, and is proportional to the distance of vibration displacement.

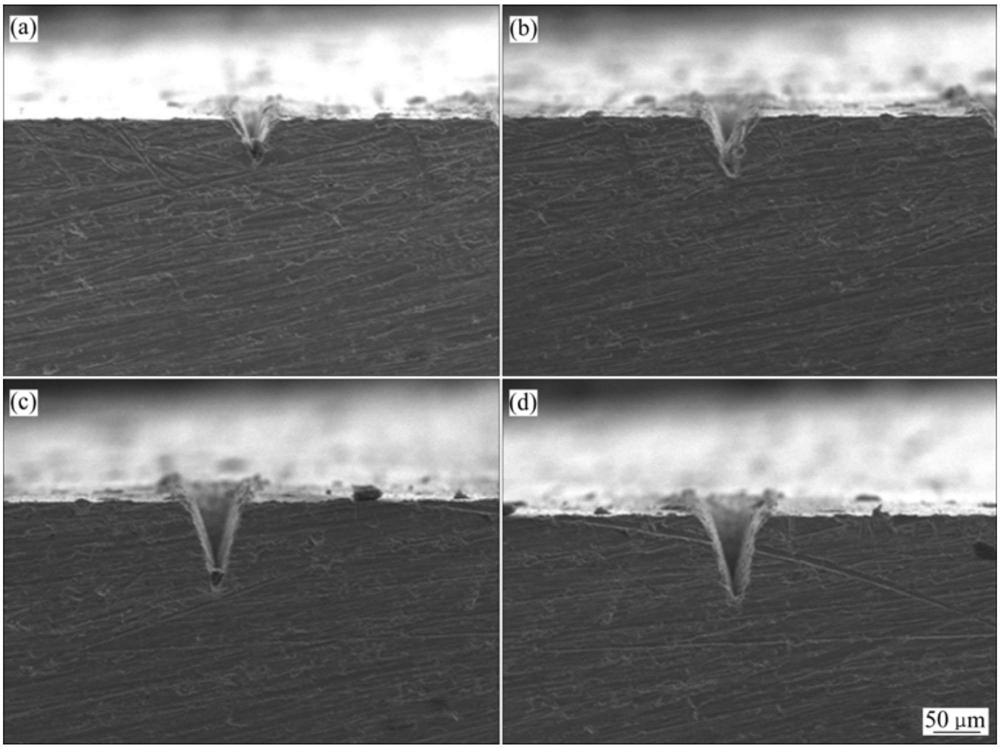


**Fig. 4** Cross-sectional SEM images of copper substrate machined with various displacement vibrations using femtosecond laser with a pulse energy of 50 μJ/pulse and scanning speed of 0.01 mm/s; (a) No vibration; (b) *D*=3.5 μm; (c) *D*=15.7 μm; (d) *D*=16.5 μm

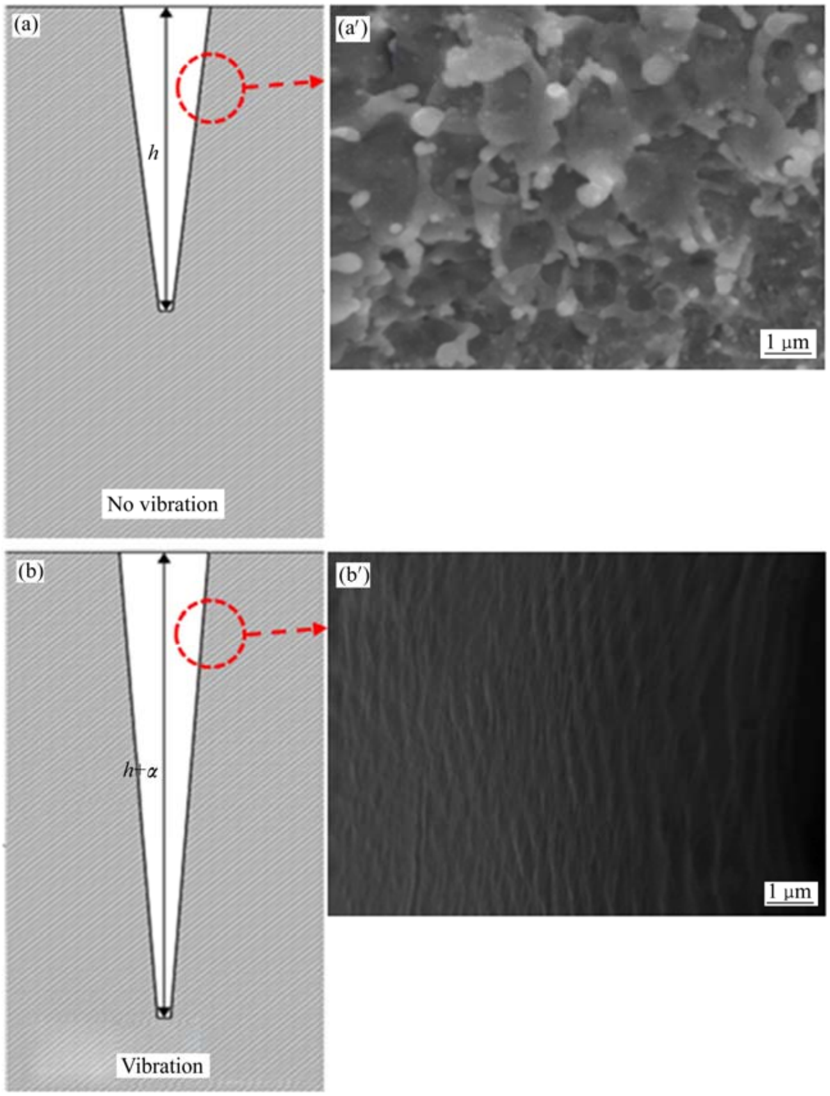


**Fig. 5** Illustration of femtosecond laser-drilled holes and SEM images of deposited materials of wall surface by femtosecond laser machining of copper substrate: (a, a′) Without vibration assistance; (b, b′) Vibration assistance

Based on our understanding of femtosecond laser interactions with metals under femtosecond laser irradiation, the energy is delivered to the material within a short time scale, and as a result absorption occurs at nearly solid-state density. The energy is firstly deposited in the electronic subsystem within a layer of thickness of tens of nanometer. The ablated material is removed from the wall surface in the form of expanding high pressure plasma. The plasma is confined close to the specimen surface at atmospheric pressure. Condensation of vapor in the plume leads to the generation of nanoparticles [11,12] which aggregate and are deposited on the wall surface of the specimen. The laser pulse accumulation plays a critical role in the formation of nano-joining [9] and nano-drpolets [5] similar to surface structures in metals. During pulse accumulation, the initial surface temperature is above the melting point, the plume is generated from the liquid phase rather solid phase. Vapor condensation starts with nucleation, proceeds with the growth of a supercritical nucleus, and comes to a halt due to quenching. In order to make nanoparticles to aggregate and form nano-sized droplet structures, a continuous supply of vapor to the expanding plume is required in order to maintain the nucleus density. The plume generated by successive laser pulses must arrive before the critical time of nucleation. The interaction between femtosecond laser pulses and a solid can have diverse effects on solid state materials, such as electron excitation, plasma generation, thermal diffusion, material ablation and shock-wave loading, and so on [9−12]. The mechanism underlying the relationship between femtosecond laser ablation and vibration of a focused femtosecond pulsed laser beam on metals is not clear. However, in the present experiment, we can remove the roughness of wall surface and increase the aspect ratio through controlling the condition of laser pulse accumulation using a vibrator [10].

## 4 Conclusions

The effectiveness of vibration of an objective lens are demonstrated on the reduction of burrs at the entrance of machined hole, improvement of the machined wall surface in micro/nano machining, and increasing the aspect ratio for machined metal are demonstrated. Compared with conventional femtosecond laser machining currently used in practical applications, the results in this experiment demonstrate the potential of utilizing a femtosecond laser for controlling the surface roughness and machined depth in fabrication work in various fields such as semiconductors, displays, and the bio-medical industry. Future work will be focused on more parametric investigations to explore the optimal laser and vibration parameters with respect to various materials.

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**(Edited by CHEN Can-hua)**