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Measurement and machining in microfabrication based on radiation pressure control

Yasuhiro TAKAYA, Satoru TAKAHASHI, Takashi MIYOSHI
(Osaka University, 2-1 Yamadaoka, Suita, 565-0871 Osaka, JAPAN
Tel/Fax: +81-6-6879-7320, E_mail: takaya@mech.eng.osaka_u.ac.jp)

Abstract: We have been developing new fabrication tools based on optical radiation pressure and related phenomena to develop a flexible and accurate microfabrication technology. In this paper, the laser trapping probe for the nano_CMM for assessment, in addition to micromachining technique using a small particle controlled by optical radiation pressure and laser aggregation technique are discussed. As the positional detection probe for the nano_CMM, an optically trapped silica particle with 8 mm diameter in forced oscillation state is used. A probe sphere retains a stable position when applied with trapping force by Nd: YAG laser light formed annular and is forced to oscillate by the driving force changed by modulating the intensity of LD emission. Experintal results show that this vibrational microprobe has the possibility to achieve positional sensing accuracy of less than 25 nm. As a new micromachining technique, nano_removal process using an optically trapped micro_grain is proposed. The laser trapping force enables not only to stably trap the diamond grain with asymmetrical shape but also to freely control the position with spinning. Using this micro machining tool, the machining experiments of hydrocarbon film are performed. AFM observation confirmed that the fine groove with depths of about 3~4 nm can be fabricated. As an additive process based on radiation pressure, a laser microstructure fabrication using laser agglomeration phenomena of colloidal particles aided by radiation pressure is investigated. By controlling laser beam scanning in slurry containing KOH solution and SiO_2 particles with a diameter of 140 nm, colloidal particles are aggregated and adhered firmly to a silicon wafer substrate. Using this laser agglomerating process, two_dimensional grid microstructures at the pitch of 5 mm can be fabricated.

Key words: radiation pressure; nano_CMM; probe; micromachining tool; micropart
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1 Introduction

Technical trends of microfabrication include increasing diversification and complexity of processes, combination of different processes, and multifunctions, as seen in various type of microsystems such as micromechanical system, microoptical system, three_dimensional LSI, MEMS (Micro_Electro_Mechanical System), MOEMS (Micro_Opto_Electro_Mechanical System), etc. Nowadays, a variety of physical/chemical material removal process technologies are used, for example, micro laser processing[1], fine electro_discharge machining[2], ultraprecision machining[3], micro_lathe machining[4] and application processes of semiconductor technology such as photo_lithography[5], etc. On the other hand, assembling and bonding technologies are becoming increasingly important with the

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widening gap between design and implementation[6], which is accompanied by decreasing minimum feature size and increasingly complicated microcomponents. The establishment of assessment technologies for three_dimensional micromachining accuracy is also an urgent issue. We have been developing new fabrication tools based on optical radiation pressure and related phenomena to develop a flexible and accurate microfabrication technology. For instance the laser trapping probe[7] for nano_CMM (Coordinate Measuring Machine) for assessment, and micromachining technique using a small particle controlled by optical radiation pressure[8] for the material removal process. The laser trapping technology[9] is useful for micro_assembling and bonding also[10]. As another approach, we also carried out a study on the aggregation and accumulation of nano_particles by laser beam irradiation on the silicon wafer surface in slurry, which contains fine Silica particles (SiO_2)[11]. The work reported in this paper mainly deals with the laser trapping probe for nano_CMM, in addition to micromachining technique using a small particle controlled by optical radiation pressure and laser aggregation technique.

2 Laser trapping probe for the nano_CMM

In order to obtain and maintain compatibility of standardized microcomponents in practical use, it is necessary to assess the geometrical properties of micromachined 3D shapes based on coordinate metrology at an accuracy of nanometer order. For this a nano_CMM which is 1/100 or 1/1000 the size of a conventional CMM has been proposed for the coordinate metrology of microparts by positional probing. Fig. 1 shows the concept of the nano_CMM. In the use of the nano_CMM, the dimensions and other geometrical properties of the microscale 3D shapes of microcomponents must be evaluated in the nanometer order by probing the measurement points using a three_dimensional sensing microprobe. The microprobe must satisfy harsh specifications such as probe sphere size in the micrometer order, 3D positional detection sensitivity of higher than 10 nm and measuring force of less than 10^{-5} N. New probing techniques for achieving nano_positional detection using a microprobe are therefore required. To answer to this need, we have developed a new probing technique for the nano_CMM, called a laser trapping probe, whose principle is based on the single_beam gradient_force optical trapping technique[13] and the vibrational technique[14] driven by radiation pressure as an active sensing method.

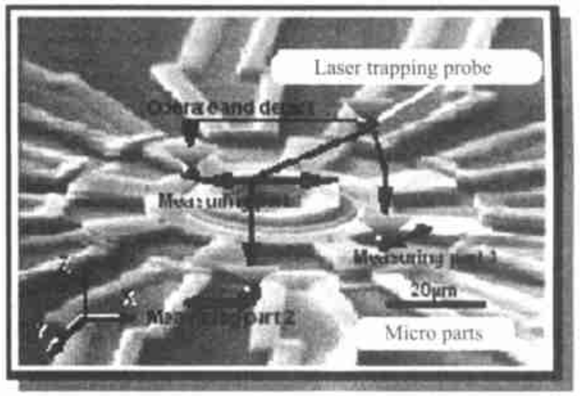


Fig. 1　Conceptual drawing of nano_positional detection using laser trapping probe

2.1 Principle of vibrational microprobe

An optically trapped small dielectric particle in air is used as a microprobe sphere shown in Fig. 2. It is sensitive to external force generated by interactions with a workpiece and has the same dynamical properties as a positional detection probe. Fig. 3 shows the principle of the laser trapping probe for nano_CMM using optically forced vibration method. As the source of the trapping beam, Nd: YAG laser light formed annular is used. The probe sphere retains a stable position against gravity when applied with trapping force (Fig. 3(a)). Improving the stability of the trap using annular beam trapping technique, a probe sphere can be forced to oscillate by the driving force exerted by radiation pressure. As the source of the driving beam, the light from the laser diode (LD) traveling through the center of the annular beam is used (Fig. 3(b)).

The driving force is changed by modulating the intensity of LD emission. An optically trapped small dielectric particle in forced oscillation state is useful for the positional detection probe (Fig. 3(c)). Consequently, a position can be detected based on changes of oscillating frequency (Fig. 3(d)).

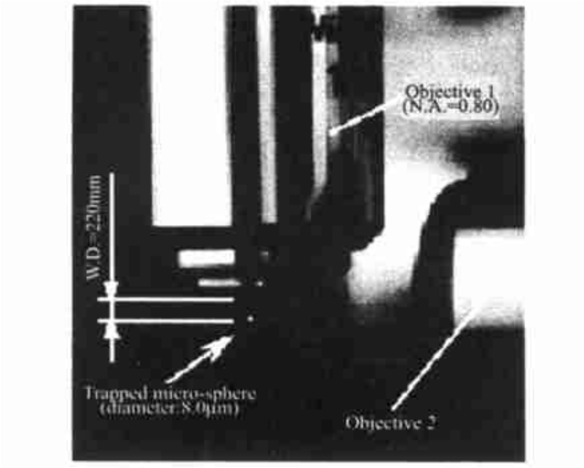
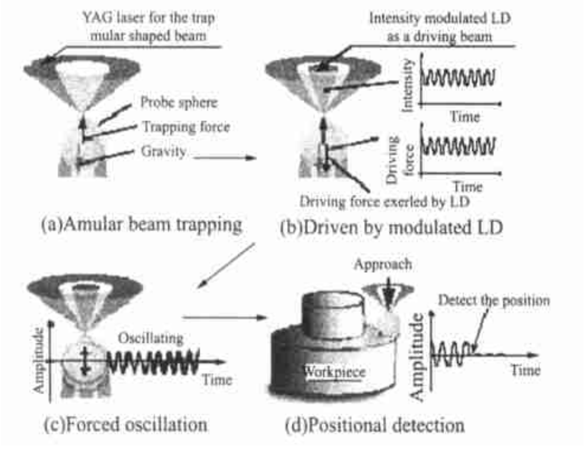


Fig. 2 Successful trapping of a silica particle in air by using an objective



(a)Amular beam trapping (b)Driven by modulated LD

(c)Forced oscillation (d)Positional detection

Fig. 3 Principle of the laser trapping probe for nano_CMM using optically forced vibration method

2.2 Vibrational microprobe system

Schematic diagram of the laser trapping probe system based on the optically forced vibration technique is illustrated in Fig. 4. The system is composed of a trapping optical system, a driving opticalsystem for optically forced oscillation of a probe sphere, a detecting optical system for monitoring the oscillating status.

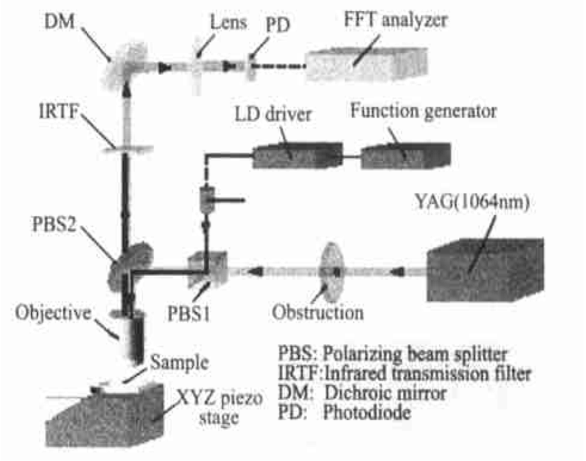


Fig. 4 Schematic diagram of the laser trapping probe system based on optically forced vibration technique

The light with wavelength of 1064nm is emitted from Q_switch/Nd: YAG laser and is annular shaped by an obstruction. The laser beam is focused by an objective with N. A. of 0.95 on a silica particle with 8#m diameter. The modulated light with wavelength of 687 nm from LD is joined with the YAG laser light. The backscattered YAG laser light from a trapped particle passes through IRTF with eliminating LD light, then detected using PD. Oscillating condition is monitored by the output signal from PD. Positioning of a workpiece is performed using an xyz_stage with positioning accuracy of 5nm, which is driven by PZT actuators.

2.3 Positional detection properties

In order to verify the performance of the vibrational microprobe as a positional sensitive probe, we conducted an experiment to approach the probe sphere to a glass microsphere with 168#m in diameter. Fig. 5 shows investigation of positional detection using the change of vibrational status of the probe sphere by approaching it to a glass microsphere. In this experiment, the probe particle is forced to vibrate at a frequency of 500 Hz. Fig. 6 shows measurement results of the peak power in Fourier spectra of the voltage output from the photodetector changing with the vibration status for verifying positional detection principle. While the probe sphere is moving from z = 0 nm to z= 4 900 nm, the spectra keeps a peak at the modulating frequency of 500 Hz. However, we can recognize that the peak vanishes at z = 4 925 nm. On the other hand, the probe sphere returns to z = 4 900 nm, then the peak appears again. These results show that our method has the possibility to have positional sensing accuracy of less than 25 nm.

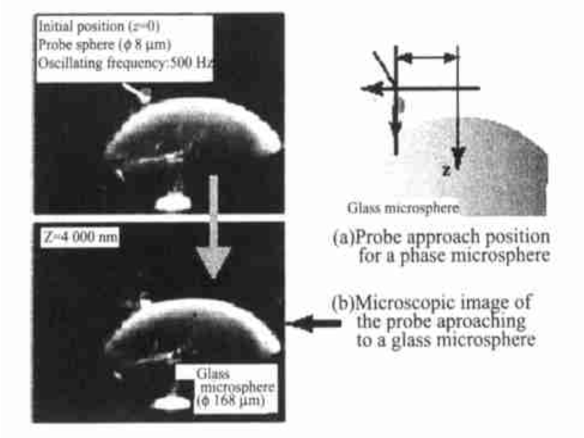


Fig. 5 Investigation of positional detection using the change of vibrational status of the probe sphere by approaching it to a glass

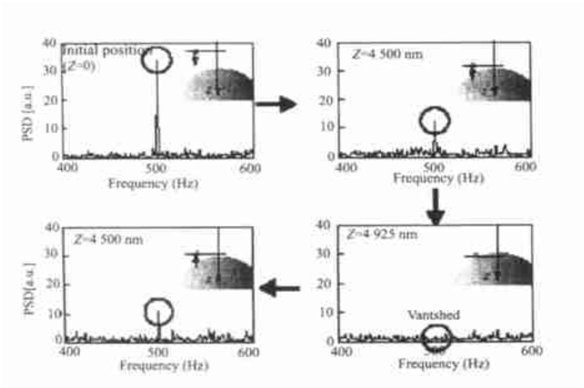


Fig. 6 Measurement results of the peak power in Fourier spectra of the voltage output from the photodetector changing with the vibration status for verifying positional detection principle

3 Micromachining technique based on radiation pressure

The work reported here deals with a material removal process and an additive process based on radiation pressure. The former is a new micro_machining using an micro_grain controled by optical radiation pressure and the latter is a laser microstructure fabrication using laser agglomeration phenomena of colloidal particles aided by radiation pressure.

3. 1 Nano_removal process using optically trapped grain

As shown in Fig. 7, if the laser trapped particle is moved, spun or oscillated by the optical radiation pressure, the micro_machining which removes the amount of atomic order, namely the depth of cut is as small as several nano meter, will be able to be performed.

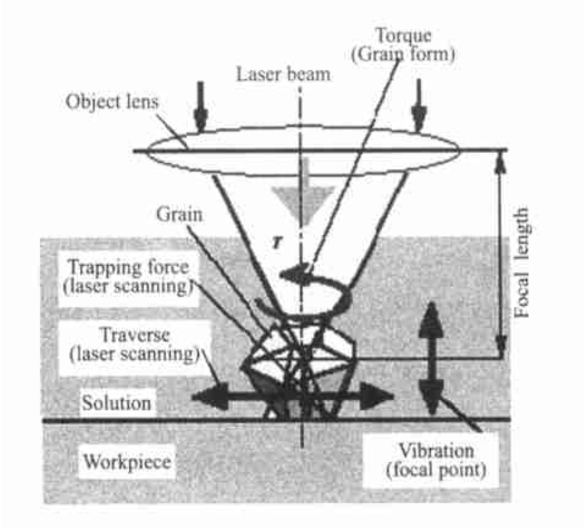
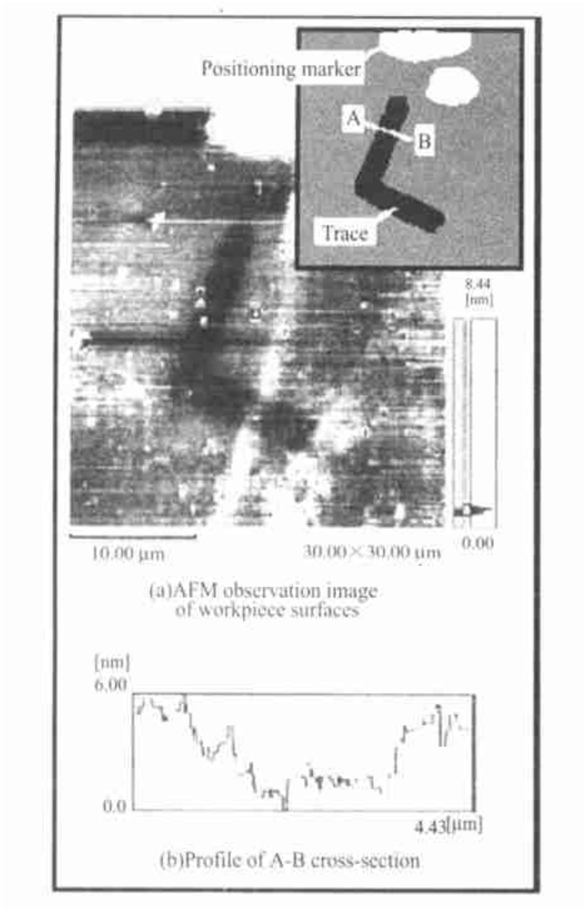


Fig. 7 Concept of optical radiation pressure micromachining

We verified the motion controllability of laser trapped particles. For the diamond grain with non_spherical irregular shape, it is not easily trapped with stability comparing with the spherical particles, however, some of the irregular shape particles are stably trapped and spun. It is considered that the non_spherical and asymmetricalparticles shape causes its spinning. The spinning ratio is up to 300 r. p. m. at high speed.

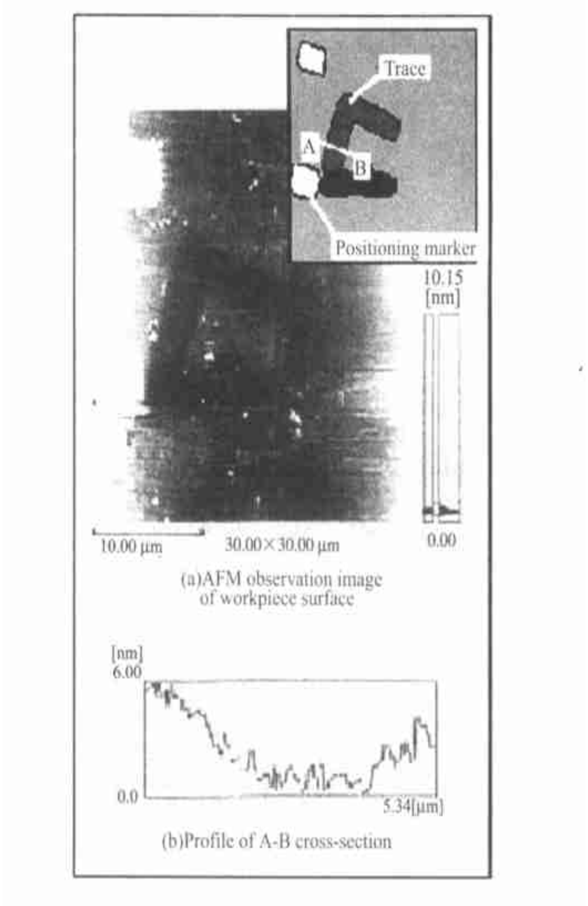


(a)AFM observation image of workpiece surfaces

(b)Profile of A-B cross-section

Fig. 8　Experiemntal results for the case of silica sphere

Next, we performed the machining experiments of hydrocarbon film. Fig. 8 and Fig. 9 show the machining experimental results obtained by AFM observation for the case of silica spheres and spinning diamond grains, respectively. The rectangular bright parts in Fig. 8(a) and Fig. 9(a) mean positioning markers which allow us to find the machining areas and the moving traces of the machining particles. The traces which look like hook are observed nearby the markers in both Fig. 8(a) and Fig. 9(a). The positions and the shapes of those traces conform to moving path of the particles. This fact shows that the trapped particle. s movement fabricates those traces on the surface of hydrocarbon film. The cross_sections of the traces are shown in Fig. 8(b) and Fig. 9(b). The groove depths are about 34 nm and 23 nm, respectively. In no rotation case of the silica sphere, the width of the trace is seen to be about 3#m narrower than the particle diameter 5#m. On the other hand, in the rotation case of diamond grain, the width of the trace is about 4#m, which is almost the same value as the average grain size 4#m. From these results, the non_spinning particle as well as the spinning particle seems to have the feasibility of micro_machining.



(a)AFM observation image of workpiece surface

(b)Profile of A-B cross-section

Fig. 9　Experiemntal results for the case of rotating diamond grain

3.2　Micro_additive process using colloidal particles aggregation

The principle of this microstructure fabrication method is based on the laser agglomerating process of colloidal particles with diameter less than the sub_micrometer order. The dynamical behavior of one particle in a focused laser beam is thought to cause concentration of colloidal particles. Focused laser light irradiated into colloidal particle solution

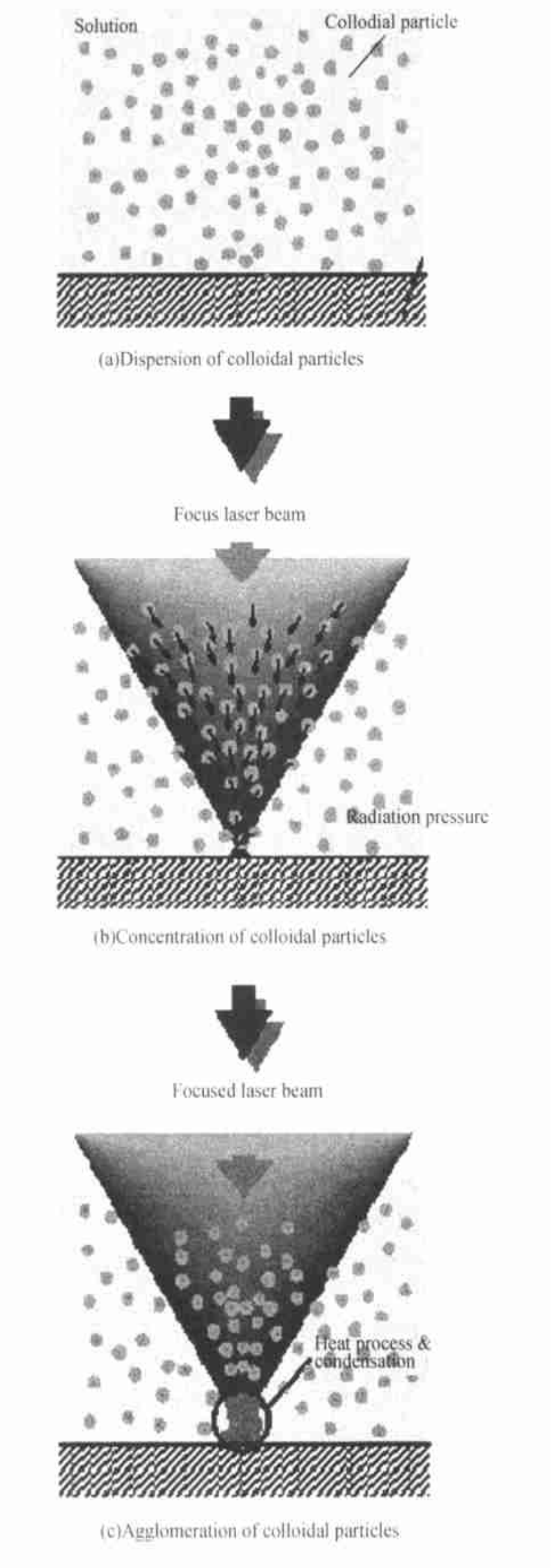


Fig. 10　Laser agglomerating process of colloidal particles

is also believed to create this situation. Fig. 10 shows the fundamental mechanism of the laser agglomerating process. In the initial state, colloidal particles are dispersed in the solution (Fig. 10(a)). When the laser light is focused above a substrate surface, each particle irradiated by the light moves to the focal point (Fig. 10(b)). At the focal point on the substrate, the complicated phenomena of both heat process and condensation is considered to take place. The concentrated laser energy causes water evaporation by heat. Condensation of particles is brought about by rapid lost of solution owing to evaporation, which binds the particles together (Fig. 10(c)). Consequently, colloidal particles aggregate and adhere firmly to the substrate.

We used silicon wafer as a work substratum, which is deposited with a thermal oxide layer of 1 000 nm in thickness and cut into 10 mm@10 mm. The power of Ar^+ laser light is controlled within a range up to 200 mW. Slurry used for laser agglomerating process contains KOH solution and SiO_2 particles with a diameter of 140 nm. By controlling laser beam scanning, we tried to fabricate two_dimensional grid microstructures at the pitch of 5#m by the laser agglomerating process. Fig. 11 shows a SEM image of a fabricated microstructure. Though certain defects and fluctuations of lines were seen, the results confirmed that the laser agglomerating process may be applicable to microfabrication.

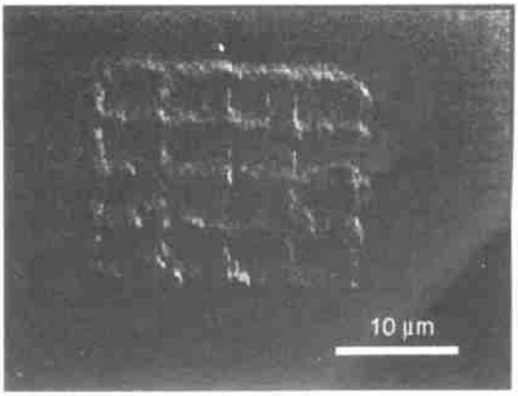


Fig. 11　SEM image of two dimensional grid microstructure fabricated using laser agglomeration process

4 Conclusions

Fundamental characteristics of the newly developed laser trapping probe introducing an optically forced vibration method were experimentally investigated. We have achieved three dimensional trapping of a microprobe sphere in air with the annular beam generated by using an obstruction. The probe sphere in annular beam trapping was oscillated using the LD laser light with the sinusoidal modulation. We suggested that our method has the possibility to have an accuracy of less than 25 nm from the measure_ments of the vibrational status while the probe sphere is approaching to the glass microsphere.

We proposed a new micro_machining technology such as a material removal process and an additive process based on radiation pressure. The laser trapping force which is as small as 0.1 nN enables stably trapping of the spherical particle. Furthermore, that force enables not only to stably trap the spinning diamond grain but also to freely control the position of the spinning grain. By traversing the laser trapped particles such as silica sphere and diamond grain on the hydrocarbon film, we observed the grain trace with the depth of several nano meter by the use of AFM. This fact suggests the feasibility of the optical radiation pressure micro_machining. The fundamental characteristics of the forming process of agglomerated marks were experimentally investigated. Experimental results show that the laser agglomerating process may be applicable as an additive process. Agglomerated marks with a thin width of about 1#m were successfully created by continuous process. By controlling the laser beam scan, it is possible to fabricate two_dimensional microstructures at micrometer order precision using this laser agglomerating process.

References:

[1] RICCIARDI G, CANTELLO M, MARIOTTI F, et al. Micromachining with eximer laser[J]. Annals of the CIRP, 1998, 47(1): 145.

[2] YU Z Y, MASUZAWA T, FUJINO M. Micro_EDM for three_dimensional cavities _ development of uniform wear method [J]. Annals of the CIRP, 1998, 47(1): 169.

[3] TAKEUCHI Y, SAWADA K, SATA T. Ultraprecision 3D micromachining of glass[J]. Annals of the CIRP, 1996, 47 (1): 401.

[4] OKANO K, WAIDA T, SUTO T, et al. Micro_grinding of micromachine parts[A]. Proc Int ABTEC(Abrasive Technology) Conf [C]. 1993.

[5] SATO K. Micromachining of 3_dimensional microstructure by etching[J]. J of JSPE, 1995, 61(10): 1373.

[6] SETER D, HERSHKOVITZ M, KALDOR S. On the gap between design and implementation of MEMS[J]. Annals of the CIRP, 1998, 47(1): 463.

[7] TAKAYA Y, SATO N, TTKAHASHI S, et al. The laser trapping probe for Nano_CMM (1st Report) _positional detection principle of the laser trapping probe and its nature[J]. Journal of the Japan Society for Precision Engineering, 2000, 66(7): 1081.

[8] SHIMIZU H, MIYOSHI T, TAKAYA Y, et al. Study on micro_machining using a small particle controled by optical radiation pressure[J]. Journal of the Japan Society for Precision Engineering, 2000, 66(6): 901.

[9] ASHKIN A. Acceleration and trapping of particles by radiation pressure[J]. Phys. Rev. Lett., 1970, 24: 156.

[10] IKENO J, SAWAKI D, MORI y, et al. New assembly technique of three dimensional micro_structure by YAG laser beam (1st Report, Proposition of fine particle manipulation and assembly technique in the air) [J]. Journal of the Japan Society of Mechanical Engineers, 1998, 627(64): 326.

[11] TAKAYA Y, KIMURA K, TAKAHASHI S, et al. Study on laser microstructure fabrication using colloidal particles

cotrolled by radiation pressure[A]. Proceedings of 2002 Japan_USA Symposium on Flexible Automation VOl. II [C]. 2002.

[12] TAKAMASU K. Basic concept of Nano_CMM[A]. Proc of The Japan_China Bilateral Symposium on Advanced Manufacturing Engineering[C]. 1996. 155.

[13] ASHKIN A, DZIEDZIC J M, BJORKHOLM J E, et al. Observation of a single_beam gradient force optical trap for dielectric particles[J]. Opt Lett, 1986, 11: 288.

[14] NISHIKAWA M, TAKAYA Y, TAKAHASHI S, et al. Probing technique for microparts using optically trapped particle by annular beam[A]. Proc of International Symposiun on Photonics in Measurement [C]. 2002. 103.