Rapid Manufacturing of 3D Micro-products using UV Laser Ablation and Phase-change Filling

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UV laser micromachining is generally used to create microstructures for micro-products through a sequence of lithography-based photo-patterning steps. However, the micromachining process is not suitable for rapid realization of complex 3D micro-products because it depends on worker experience. In addition, the cost and time required to make many masks are excessive. In this paper, a more effective and rapid micro-manufacturing process, which was developed based on laser micromachining, is proposed for fabricating micro-products directly using UV laser ablation and phase-change filling. The filling process is useful for holding the micro-products during the ablation step. The proposed rapid micro-manufacturing process was demonstrated experimentally by fabricating 3D micro-products from functional UV-sensitive polymers using 3D CAD data.

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1. Introduction

Typical micro-manufacturing processes are performed on silicon substrates. These processes can be subdivided into additive, subtractive, and hybrid processes, such as surface micromachining, bulk micromachining, and LIGA (LIthographie–Galvanik (electroforming)–Abformung (molding)) processes, respectively. Three-dimensional micro-parts and structures are fabricated using lithographic processes that require the repeated use of a sequence of masks, which demand considerable manufacturing time and expense to produce. The cost of a mask may be minimized in a mass production process because a single mask generates a batch of micro-parts on a wafer. However, most micro-parts must be manufactured quickly in small lots for trial tests before the mass production stage. The design specifications and modeling methods of new micro-parts are currently restricted because it is not possible to follow a perfect design method to produce many micro-parts without relying on trial and error. In order to save on the manufacturing cost and time, a new technology for rapid micro-manufacturing is required.[1,2] In addition, the setup procedure required for rapid micro-manufacturing of three-dimensional microstructures using laser micromachining is difficult to automate because it is time consuming. A more effective setup method would greatly reduce the micro-manufacturing time due to the large percentage of the total time consumed by these processes.

In general, the setup processes for the workpieces fall into one of three categories, which involve the bed of fingers on the table itself, the fluidized bed, or the phase-change introduced to hold the workpieces.[3]

In this paper, the flexible work-holding processes obtained using a phase change are examined to fully show the potential of high-speed micromachining three-dimensional micro-parts. The micro-parts are first enveloped by a low-melting point material in its liquid state, which is then solidified by the heat exchange arising from natural convection and conduction. Thus, the micro-parts are quickly fixed in place by the work-holding force of the phase change. The process parameters, such as the laser power, machining speed, and material properties, are experimentally investigated to obtain the optimal conditions for laser micromachining. The proposed process described in this paper is very useful for rapidly fabricating three-dimensional microstructures of various materials at low cost during the design stage.

2. Experimental system

A Q-switched $Nd:YVO_4$ diode pumping solid-state (DPSS) laser made by Coherent, Inc. in the United States was used for this study. A solid-state laser does not use toxic gas so that its operating conditions are safer than those of a gas laser. In addition, its cost is less than that of a gas laser because the system is compact.

The laser system is illustrated in Fig. 1. It consisted of many optical components such as beam expanders and mirrors, measuring equipment, X–Y stages, a personal computer, a monitoring system, a laser source, and a control system. The laser source radiated a collimated coherent beam at a wavelength of 1,064 nm in pulsed or continuous waves. By using a nonlinear optical crystal such as KH_2PO_4 (KDP) or KD_2PO_4 (KD^*P), the fundamental harmonic wavelength (λ_1 = 1,064 nm) could be converted into the second harmonic wavelength (λ_2 = 532 nm) or the third harmonic wavelength (λ_3 = 355 nm).[4] A laser beam, which can have various wavelengths ranging from infrared to ultraviolet light, is useful for processing various types of materials, but the specific wavelength must be selected according to the material because the absorption coefficient of the material is greatly affected by the given wavelength.

In this study, the third harmonic wavelength of 355 nm was used to fabricate the micro-parts. The minimum spot diameter, or line width, was calculated from the numerical aperture (NA) of the optical system and the wavelength of the laser beam. The minimum line width of this laser system was 10.83 μm for NA = 0.04 and $\lambda = 355$ nm. We used computer-aided design and computer-aided manufacturing (CAD/CAM) for three-dimensional laser micromachining to generate beam paths for the minimum line width and to control the position and the movement of the X–Y stages and the shutter signal of the laser system.[5]

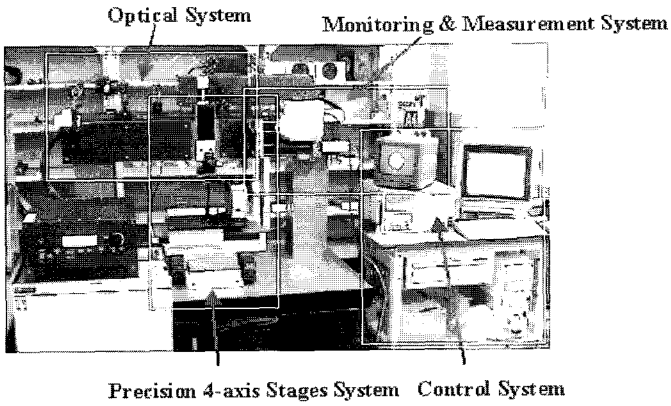


Fig. 1 Laser micromachining system, including an optical system, a monitoring and measurement system, a precision alignment unit, a control system, and a laser source

3. Rapid micro-manufacturing process

The rapid micro-manufacturing process proposed in this paper is a new method that combines laser ablation with a work-holding technique that uses low-melting point materials. This process has some advantages over other rapid manufacturing processes. A successful rapid micro-manufacturing process must solve the gap problem between layers, which is a critical issue in stereolithography (SLA), and not only overcome the limit of material usage but also directly realize micro-parts from various functional polymers. The rapid micro-manufacturing procedure proposed in this paper is illustrated in Fig. 2.[6] During this process, the upper surface of the workpiece is first machined by laser ablation. Then the cavity of the upper surface is filled with a low-melting point material, such as liquid wax. After the liquid changes to a solid, just before the holding cavity and the remaining parts are to be machined, the workpiece is turned in the opposite direction and laser micromachining is applied to the lower surface in sequence. Finally, the three-dimensional micropart is obtained after a short manufacturing time by dissolving the wax.

This manufacturing procedure is very similar to high-speed rapid prototyping (HiSRP), which was developed based on high-speed mechanical machining using a low-melting point metal.[7,8]

The only difference is that the high-speed machining is replaced by laser ablation. Bismuth alloys perform well as work-holding filling materials in HiSRP since they have a melting point of 140 °C compared to 660 °C for aluminum. Wax was chosen to hold the polymer micro-parts for the laser micromachining because wax can be melted at 65 °C and separates well from the polycarbonate (PC) polymer.

3.1 Laser ablation

Laser micromachining requires sufficient absorption in the

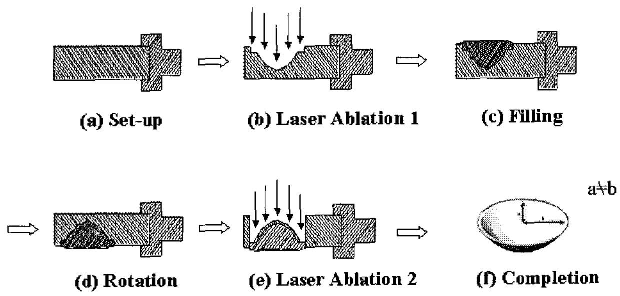


Fig. 2 Laser rapid micro-manufacturing process

surface region of the processed materials. The absorption coefficient is defined by the irradiation wavelength.[9] Various wavelengths, from infrared to ultraviolet, can be used to fabricate microstructures. The choice of material to be processed will determine the wavelength required to obtain optimal micromachined results.[6] In this experiment, we selected PC as the machining target since PC is more sensitive to a 355-nm wavelength than other polymers. During laser ablation, a high-intensity laser beam is irradiated on the surface of the polymer, photon energy is absorbed up to the penetration depth, and the polymer is vaporized before finally melting. The generated plasma spreads out in the air and sticks on the surrounding bur edges, forming a halo during the short manufacturing period. The relationship between the damage threshold and the laser pulse width is known for some materials. Fig. 3 shows that the experimental results could be controlled linearly according to the ablation depth and number of pulses number during the UV laser irradiation.

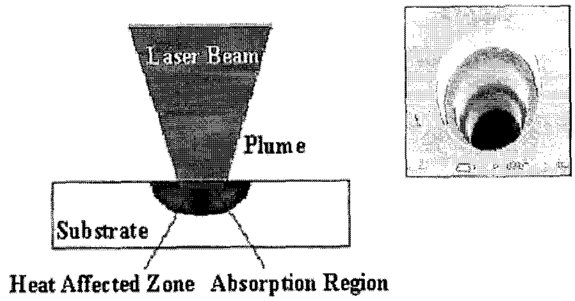


Fig. 3 Principle of UV laser ablation

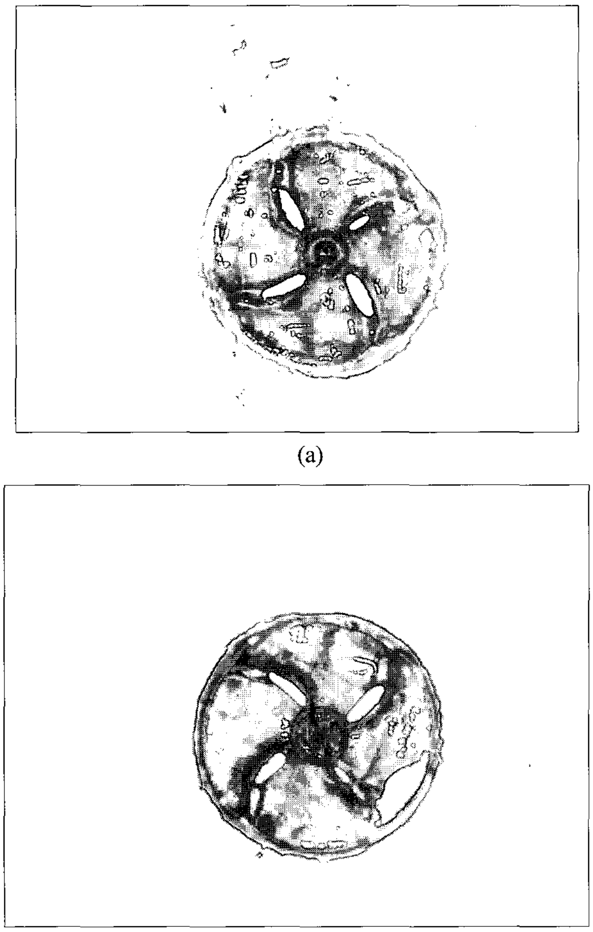
The ablation depth per pulse can be predicted because the relationship between the ablation depth and the number of pulses is known from previous studies. For example, polymer ablates 0.3 to 0.7 μm/pulse, ceramics and glass ablate 0.1 to 0.2 μm/pulse, and metal ablates 0.1 to 1.0 μm/pulse. Automated CAM programs for fully three-dimensional micro-shapes work on the basis of optimal processing conditions. Thus the fundamental experiment is very important to ensure the accuracy of the machined dimensions. Previous studies have shown that the best machined cross-profile of PC is obtained for a laser energy density of 0.053 J/cm^2 using 13 multiple-scan steps. The minimum line width is about 20 μm. This value is slightly greater than the theoretical value because a wider line width is influenced by the thermal ablation effects. To obtain a cleaner machined surface, each scan step is required to overlap with the next scan step. The best optimal overlapping rate is 20 % for a scan speed of 60 mm/s.[10]

3.2. Phase-change filling

Current work-holding processes are time consuming and not automated when three-dimensional micro-parts are machined using laser micromachining. Therefore, the phase-change filling method was examined in this paper. This method is more flexible for arbitrarily shaped micro-parts. The filling liquid infiltrates the cavities of the workpiece, and the work-holding force is created as soon as the liquid changes to a solid. The procedure is quite simple. First, the upper side of a three-dimensional micro-part is processed using laser ablation. The depth of the ablation is controlled linearly. Then the machined cavity is enveloped by the phase-change filler and the lower side is machined using laser ablation. After all the machining is finished, fully three-dimensional microstructures are obtained by melting the solid-state filler. This process has some advantages over maskless and rapid micro-manufacturing.

PC material was selected for our tests because it has superior optical properties compared to other polymers. PC is not only more sensitive to a laser wavelength of 355 nm, but it also melts at a high temperature. The solidification force of the filling material inside the cavities was quite strong during the laser ablation, and there was no separation due to the laser impact force or any melting effects. Wax has a low-melting point, and it reacts strongly to the thermal effects of ablation during laser irradiation. In our test, the wax melted at 65 °C without any heat deformation in the micro-parts because the melting and glass transition temperatures of PC are 220 °C and 160 °C, respectively. The work-holding method provided a superior micro-product quality and minimized machining errors. We could obtain the final micro-product by using water heated to 85 °C. The solidified wax separated easily after dipping the machined micro-parts into hot water. Heat deformation dimensional errors in the micro-parts were not observed when separating the finished micro-parts from the wax.

A finished microscale fan product, separated from the filling material, is shown in Fig. 4. As shown in the figure, some of the wax material remained on both the upper and lower sides. The wax separated entirely from the micro-part after a few minutes of ultrasonic cleaning with water heated to 85 °C, yielding clean machined surfaces.



(a)

(b)

Fig. 4 3D microscale fan product after separating the filling material: (a) upper face, (b) lower face

4. Experimental results and application

It is important to determine the laser process parameters before processing the fully three-dimensional micro-parts. We used the processing conditions from previous studies: a machining scan speed 60 mm/s, a machining minimum line width of 15 to 20 μm, and a scan overlapping rate of 20 to 50 %. Based on these fundamental experiments, the three-dimensional upper faces of a micro-fan were obtained as shown in Fig. 5. We had hoped to obtain a smaller micro-fan, but this would require a new polymer designed to be more sensitive to UV laser irradiation, which has not yet been developed. To verify the feasibility of the proposed rapid micro-manufacturing method, we produced a three-dimensional micro-fan with a diameter of 1.0 mm. An ultraprecision microscope was especially designed and installed to align the machining axes of both the upper and lower surfaces when the micro-part was turned 180°. The total manufacturing time was estimated at 7 h, including the time required for the wax to separate from the micro-part. As described above, an ultrasonic cleaning process with hot water was more effective at separating the solidified wax from the micro-part. The experimental results verified that laser ablation with phase-change filling was very effective at manufacturing micro-parts. We could fabricate a micro-part from a functional polymer, such as PC. The proposed process suggests a solution to the difficult flexible fixturing problems encountered while attempting to work-hold a micro-part, without the side effects caused by heat transfer from high-powered laser irradiation. The finished micro-fan, shown in Fig. 6, was rapidly fabricated using the laser micro-manufacturing process proposed in this paper, thereby demonstrating the feasibility of obtaining three-dimensional micro-parts from a functional polymer using three-dimensional CAD data with free surface geometries.

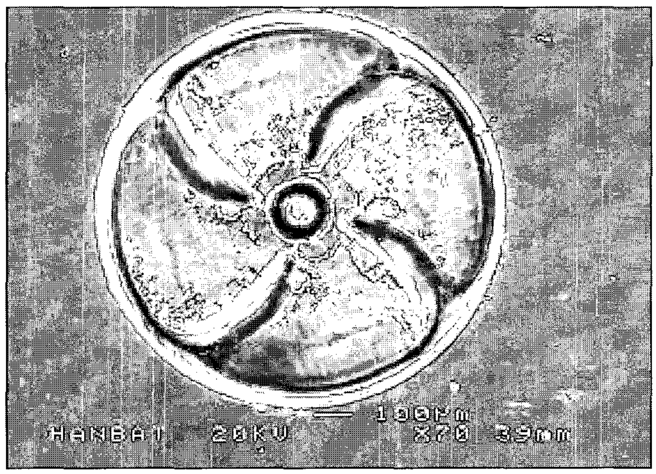


Fig. 5 3D microscale fan product after upper-face micromachining

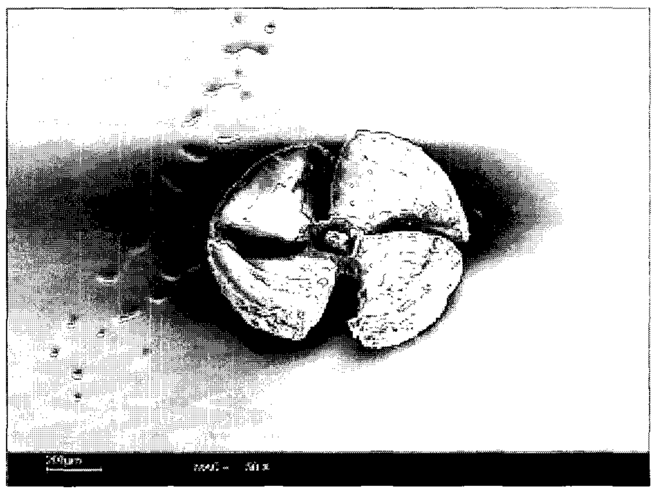


Fig. 6 Finished 3D microscale fan product

5. Conclusions

The results of this study can be summarized as follows. First, we proposed a new rapid micro-manufacturing process to produce fully three-dimensional micro-parts. This process was developed based on laser micromachining and phase-change filling using a low-melting point material. Second, the proposed process was demonstrated by fabricating three-dimensional micro-fan products from functional polymers using only a short period of manufacturing time. Smaller micro-products could also be fabricated using this proposed method if polymers more sensitive to UV laser irradiation are developed. The laser micromachining CAD/CAM program used for this study was able to control the scan-overlapping rate during the laser ablation to achieve excellent machined surfaces.

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