Laser-Based Meso/Micro Rapid Manufacturing System

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Abstract:

The meso/micro layered manufacturing technologies have significant implications for the design and fabrication of complex miniature structures. A laser-based additive/subtractive Rapid Manufacturing system is thus developed to build meso/micro structures. By incorporating laser microdeposition and micromachining with a pulsed Nd:YAG laser that has four harmonic wavelengths, this manufacturing system takes computer-aided design (CAD) output to reproduce meso/micro components in a wide selection of materials. To precisely deposit micro/nano powders and to control composition in-situ, an ultrasonic-based micro powder-feeding mechanism is developed. This additive/subtractive micro/meso manufacturing technology provides a platform for a solid integration from CAD to the realization of complex 3D miniature parts.

1. Introduction

In this paper, mesoscale is defined as the feature size from 100 µm to 10 mm while microscale is from 100 nm to 100 µm.

Mesoscale manufacturing technologies have significant implications for the design and fabrication of mesoscale devices, which can perform faster and smarter with high precision, filling the voids of 2D microscale silicon surface micromachining and LIGA, and 3D macroscale miniature machining. Meanwhile, micro components with high aspect ratios, complex geometries, and complex microstructures are essential in many applications and can deliver a new generation of functionality and performance. However, silicon-based micro-electro-mechanical-system (MEMS) techniques are two-dimensional (2D) processes with multiple steps and require complex processing procedures in a cleanroom environment. Only a limited number of materials can be processed by these techniques. With 2D processes, it is very difficult, if not impossible, to fabricate an enclosed volume of arbitrary shape and composition without the use of microassembly. MEMS should not only be built in three-dimensions (3D) but should also use a wider selection of materials, including alloys, polymers, ceramics, and heterogeneous materials.

In the last decade, Solid Freeform Fabrication (SFF) has emerged as a popular manufacturing technology for accelerated product creation [1,2]. Research has been directed at efforts that use several layered manufacturing processes to create 3D meso/micro scale structures. Micro-Stereolithography has been extensively studied and complex 3D microstructures have been demonstrated [3-6]. Movable microstructures were made by the use of two-photon 3D microfabrication with submicron resolution. EFAB (Electrochemical FABrication) specializes in fabrication of dense meso/micro metal parts by electroplating [7].

However, these micro SFF processes are not suitable to build 3D heterogeneous structures due to their limited flexibility in changing material composition in situ.

Laser-assisted Shape Deposition Manufacturing (SDM) was developed to fabricate macro scale structures [8,9]. Unlike most additive SFF processes, SDM uses sequential *additive* (deposition of part materials and sacrificial materials) and *subtractive* (material removal) steps to form 3D structures. Silicon-based MEMS and SDM processes both integrate additive and subtractive processes and use part and sacrificial materials to obtain functional structures. SDM allows control of material placement and properties in 3D space. SDM has been used to build complex 3D macro shapes with internal cooling channels, parts with continuously varying material properties, mechanisms, and heterogeneous parts with embedded sensors and actuators. If we adapt SDM methodology to meso/micro fabrication, it becomes possible to create functionally and geometrically complex meso/micro components in a rapid fashion. To scale the SDM process down to the meso/micro world, it is essential to use tools that are capable of realizing both additive and subtractive processes at micro scale.

2. System development

Lasers have been used for heating, melting, and ablation. Extensive work has been done in the arena of laser micromachining and microdeposition. Laser micromachining relies on the process of ablation [10]. Laser micromachining, especially with an excimer laser, has been used on a wide range of materials (polymers, ceramics, semiconductors, and metals) [11-14]. In recent years, frequency-tripled or quadrupled Nd:YAG lasers at wavelengths of 355 nm and 266 nm have been used for micromachining of different materials [15-18]. While laser micromachining is a subtractive process, laser microdeposition is an additive process. Laser Particle Guidance (LPG), developed by Reen [19], can deposit materials at 10 μm line width. MAPLE DW can deposit materials (polymers, ceramics, and metals) with a resolution around 10 μm [20]. Thus, a laser-assisted meso/micro process can be developed to integrate additive (laser microdeposition) and subtractive (laser micromachining) processes to form 3D heterogeneous meso/micro structures. Laser based additive/subtractive processes offer many advantages, including: no contact with substrate, no chemicals, flexible feature size and shape, high precision, and work in air at room temperature.

2.1. System design

The meso/micro rapid manufacturing system is depicted as in Figure 1. A pulsed Nd:YAG laser (20Hz at all four harmonic modes), model PRO-290-20-NRF from Spectra-Physics, serves as a *micro additive and subtractive tool*. The energy levels are: 1.97 J/pulse at 1064 nm, 0.995 J/pulse at 532 nm, 0.51 J/pulse at 355 nm, and 0.175 J/pulse at 266 nm. A laser beam attenuator is used to control laser intensity. Moreover, a PC-controlled three-axis micro-stage, LW-7 XY and Anoride 7-4 Z from Anorad Inc., with a 30-nanometer resolution and a speed of up to 200 mm/s is also implemented. The CNC-2000 software accepts G-code that is generated by the UNIGRAPHICS CAD/CAM software to control the movement of the micro-stage. The pulsed laser can be controlled spatially and temporally to obtain precise micro deposition and machining. An optical system consisting of a CCD camera and a monitor is employed to monitor

the micro-fabrication process with a maximum magnification of 3200X. Image acquisition hardware and software from National Instruments are installed in a Dell PC. In addition, an ultrasonic-based micro powder-feeding mechanism is developed and implemented to deposit micro/nano powders. The ultimate goal of this micro-manufacturing system is to provide a solid foundation for a seamless integration from CAD to the realization of complex 3D meso/micro components in a wide selection of materials.
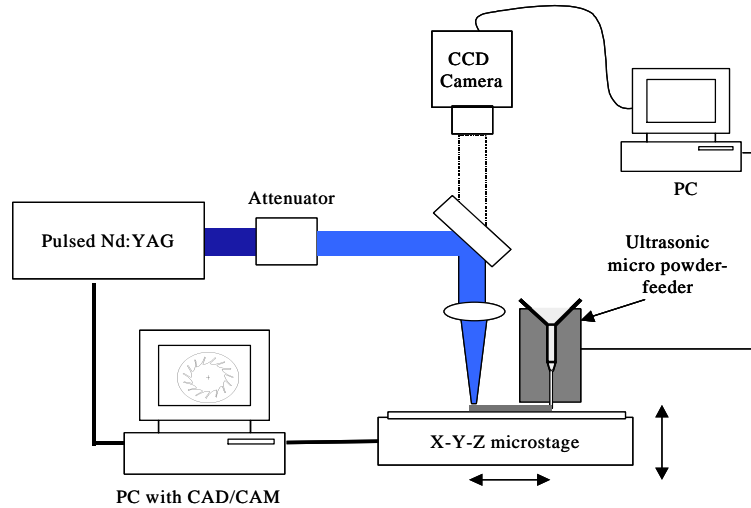

Fig.1. Laser-based micro-manufacturing system

2.2. Development of micro powder-feeding mechanism

Current laser-assisted SDM uses powder feeders and feed nozzles (with an inner diameter in the order of one millimeter) to control the material composition by mixing various powders (normally larger than 50 microns). Linoya *et al.* suggested that a vibrating system is more suitable to feed dry powders in sizes less than 100 microns [21]. Much finer powders (for instance, less than 10 micrometers) could form agglomerates that prevent continuous feeding through a capillary tube. Ultrasonic vibration has been investigated to assist the feeding of fine powders [22-25]. Capillary tubes with approximately 500-micron inner diameter have been studied to feed submicron alumina powders at rates of milligrams per second. Ultrasonic vibration at 20 kHz was generated by a piezoelectric transducer and applied to the capillary tube. It was observed that spherical powders flowed better than irregular shaped powders.

In this study, an ultrasonic-based micro powder-feeding device was developed to deposit dry micro powders. Figure 2 shows the schematic of the experimental setup. A micro capillary tube with tapered hole was assembled into a small aluminum block. A PZT plate, from Piezo System Inc., was glued on the top surface of the aluminum block. As a feasibility test, a low-cost micro capillary tube with an inner diameter of 125 μm or 50 μm and a length of 16 mm was used due to commercial availability. A function generator and a power amplifier were used to control the frequency and amplitude of the ultrasonic wave, which was generated by the thin PZT plate. It was detected that the resonant frequency of the PZT plate was 49KHz. Thus, an ultrasonic wave of 49 KHz was applied to feed dry powders through the capillary tube. The ultrasonic wave was

effectively coupled into the glass capillary from the aluminum block with a tight fit. A video microscope system was used to study the mechanism that governs the micro feeding of dry powders. Lines of dry micro powders are shown in Figure 3.
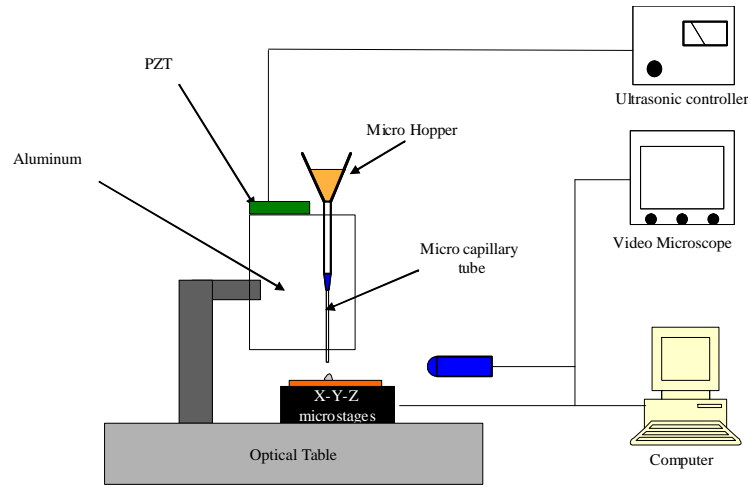

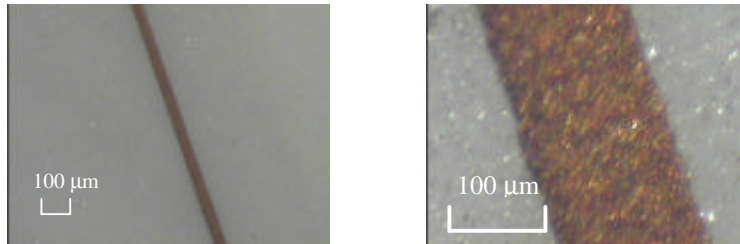Fig.2. Experimental setup for ultrasonic-base micro powder-feeding

Fig.3. Images of deposited lines of dry micro powders

The powder flow rate is important for meso/micro deposition since it can affect the continuation, width, and thickness of a deposited powder line. To measure the flow rates, a highly sensitive electric-balance was used to measure the mass of discharged powders. Powder flow rates for spherical copper powders (3 μm nominal in diameter), Invar (less than 20 μm in diameter), and stainless steel powders (3 μm nominal in diameter) were presented against the voltage applied on the PZT plate, as shown in Figure 4. Continuous discharge of micro powders was achieved at a flow rate of approximately 10^{-5}g per second. For the capillary tube with an inner diameter of 125 μm, the flow rates increase as the applied voltage increases until the voltage reaches approximately 280 V. However, the flow rates decrease quickly as the applied voltage surpasses 280 V. This is probably caused by saturation and higher temperature induced in the PZT plate at higher voltages. The difference in the flow rates for different powders might have resulted from the difference in their properties. For the capillary tube with an inner diameter of 50 μm, the flow rates, which are almost one order lower than those from the capillary tube with the inner diameter of 125 μm, increase as the applied voltage increases until the voltage

reaches approximately 220 V. However, the flow rates decrease quickly as the applied voltage surpasses 220 V.

(a)   (b)
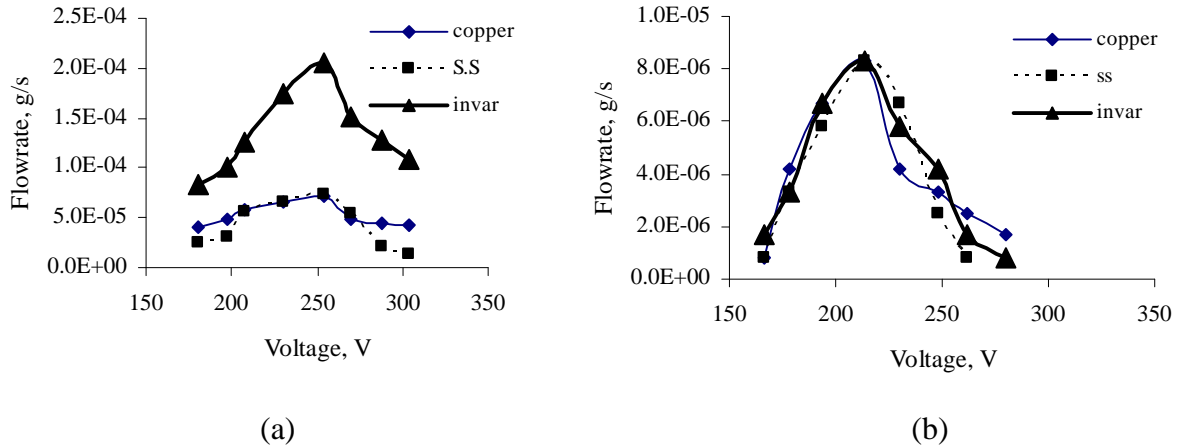
Fig.4. Powder feed rate through capillary tubes with different inner diameter
(a) Through capillary tube with an inner diameter of 125 μm
(b) Through capillary tube with an inner diameter of 50 μm

When the capillary was placed horizontally or tilted upward, powders were still discharged, as shown in Figure 5. This phenomenon verified that the powders were driven to the feeding tip of the capillary tube by friction and adhesive forces instead of by gravity. We believe that the micro feeding system can be further developed to feed powders through capillary tubes with smaller inner diameters (10~25 μm).
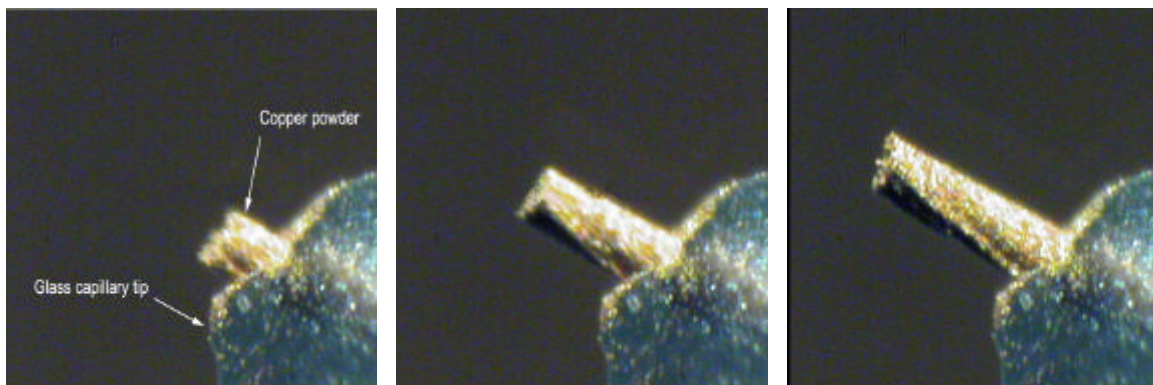

Fig.5. Images of powder feeding through an upward-tilted capillary tube

3. Experimental study

This paper presents initial experimental results on the study of meso/micro manufacturing using this newly developed system.

3.1. Study of laser micromachining

Laser micromachining was studied with laser beams at wavelengths of 355 nm and 266 nm. An optical lens with a nominal focus length of 135.3 mm for the wavelength of 355 nm and 128.9 mm for the wavelength of 266 nm was used to focus the input laser beam. The diameter of the input beam was controlled to vary the focus spot size. Laser micromachining was carried out on both stainless steel 316L (0.792 mm thick) and copper foils (0.813 mm thick). All experiments were completed in air.

Laser intensity (also called "laser fluence") and the wavelength of the laser beam can significantly affect the depth of micromachining on various materials. Thus a single laser pulse with a controlled intensity at 355 nm and 266 nm respectively was used to study laser intensity- and wavelength-dependence of micromachining on stainless steel and copper. Experimental results are shown in Figure 6.

For stainless steel machined by the laser beam of 355 nm, the micromachined depth increases rapidly with laser intensity after the ablation threshold until approximately 30.0 J/cm^2. Then ablation rates remain almost constant, approximately 0.8 μm/pulse, until the laser intensity increases to approximately 100.0 J/cm^2. The ablation rates then increase rapidly again, continuously with the increasing laser intensity. Similarly, for stainless steel machined by the laser beam of 266 nm, the micromachined depth also increases rapidly with laser intensity after the ablation threshold until approximately 40.0 J/cm^2. Then ablation rates remain almost constant, approximately 0.55 μm/pulse, as the laser intensity increases until up to approximately 120.0 J/cm^2. The ablation rates then increase continuously again with increasing laser intensity.

For copper machined by the laser beam of 355 nm, the micromachined depth increases rapidly with laser intensity after the ablation threshold until approximately 12.5 J/cm^2. Then ablation rates still increase slowly, until the laser intensity reaches approximately 170.0 J/cm^2. The ablation rates then increase at a slower speed with increasing laser intensity. Similarly, for copper machined by the laser beam of 266 nm, the micromachined depth also increases rapidly with laser intensity after the ablation threshold until approximately 10.0 J/cm^2. Then ablation rates still increase slowly, until the laser intensity reaches approximately 163.0 J/cm^2. The ablation rates then increase at a slower speed with increasing laser intensity.

The relationship between the number of laser shots at selected laser intensity and the depth of the hole machined is shown in Figure 7. The drilled depth is almost linearly proportional to the number of laser shots for stainless steel and copper at both laser wavelengths. A resolution of less than 200 nm per pulse for stainless steel and copper can be achieved. This allows accurate control of the depth of drilled holes.
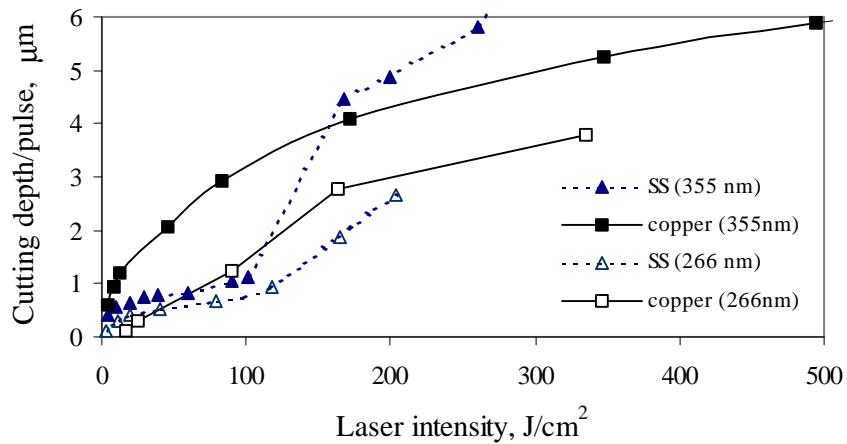
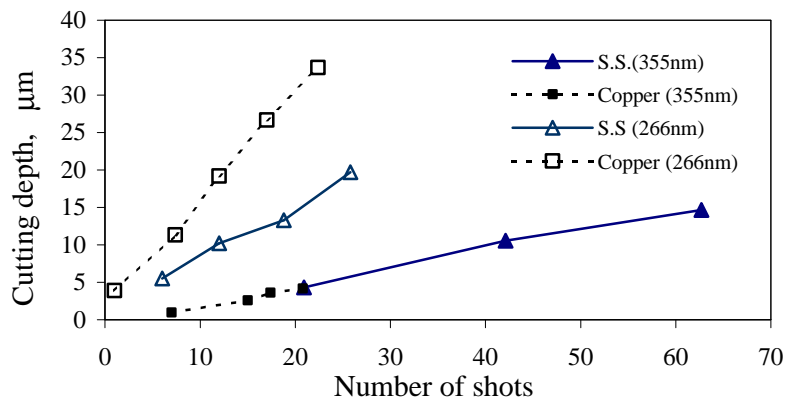Fig.6. Relationship between laser intensity and micromachined depth

Fig.7. Relationship between number of laser shots and cutting depth
(Laser intensity: 30.56 J/cm^2 at 355 nm and 102.10 J/cm^2 at 266 nm for stainless steel, 2.32 J/cm^2 at 355 nm and 90.32 J/cm^2 at 266 nm for copper)

With its focal plane on the bottom surface of the stainless steel and copper foils, laser beam at 355 nm and 266 nm was used to fabricate micro structures with high-aspect ratios, such as micro springs and actuators, as shown in Figure 8.
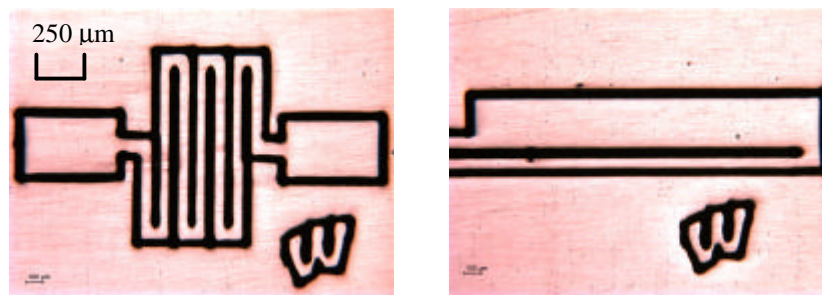

Fig.8. Micro spring and micro electrothermal actuator fabricated by laser micromachining

3.2. Study of laser microdeposition

Laser microdeposition is a process in which micro powders are fused or sintered by a laser beam. Optical absorption is critical for the deposition process. To achieve better absorption for metallic powders, a laser beam with a wavelength of 532 nm was used. The laser beam spot size on the powder layer can be controlled by input beam size on the focus lens or position change of the focus lens. In this initial study, the laser beam diameter on the focus lens was set to 3.0 mm. The nominal focal length of the focus lens is 139.8 mm for the wavelength of 532 nm. Laser beam spot with a diameter of 140 μm was obtained.

The laser scanning speed is important since it defines the interactive time between the laser beam and the micro powder layers. Laser intensity is also vital for the laser microdeposition. High laser intensity can blow the dry micro powders due to a high recoil force generated by interaction between the laser beam and the powders. On the other hand, low laser intensity cannot fuse or sinter the micro powders.

3.2.1. Microdeposition of copper powders

Numerous trials were performed to obtain optimized parameters for high quality deposition of micro powder layers. The micro powder layers of approximately 125 μm wide and 50 μm thick were baked at 180 °C for three hours, allowing powders to stick on the alumina substrate. Baking the micro-powder before laser irradiation was able to lessen the blowing of micro powders. Uniform and smooth shape of sintered layers, as shown in Figure 9, were achieved by five paths of laser scanning at laser intensity of 0.5 J/cm^2, followed by one more scanning path at laser intensity of 0.75 J/cm^2. The thickness of layers shrank to half of their original size due to the sintering that produced denser layers and also some blurs on the edge of layers.
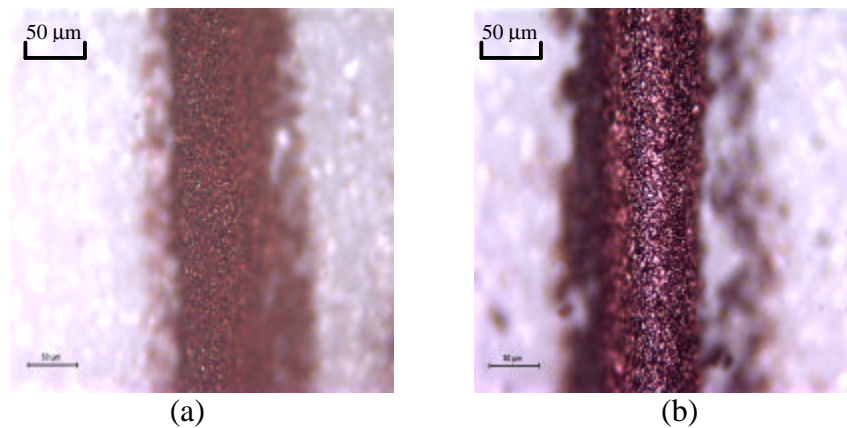

(a)   (b)

Fig.9. (a) Copper powder line delivered by the ultrasonic micro powder-feeding system
(b) Copper powder line after laser sintering

3.2.2. Microdeposition of stainless steel powders

The diameter of stainless steel powders is approximately 3.0 μm. The micro powders were delivered on the alumina plate to form patterns by using the ultrasonic micro powder-feeding system. The diameter of laser beam spot on the layer of micro powders was set to140 μm.

Straight, spiral, and wave lines of approximately 200.0 μm wide and 100 μm thick were fabricated, as shown in Figure 10. The length of straight lines is 5.0 mm. The final diameter of the spiral lines is 2.4 mm. The wave patterns consist of half circles with a radius of 200 μm and straight lines of 500 μm length. The drawing of all patterns was made with AutoCAD and then the CAD drawing was converted into G-code. All lines and patterns were baked in a baking oven at 180 °C for 11 minutes. This condition allowed the micro-powder to stick to the substrate. Baking the micro-powder before a laser irradiation was able to lessen the blowing of micro powders.
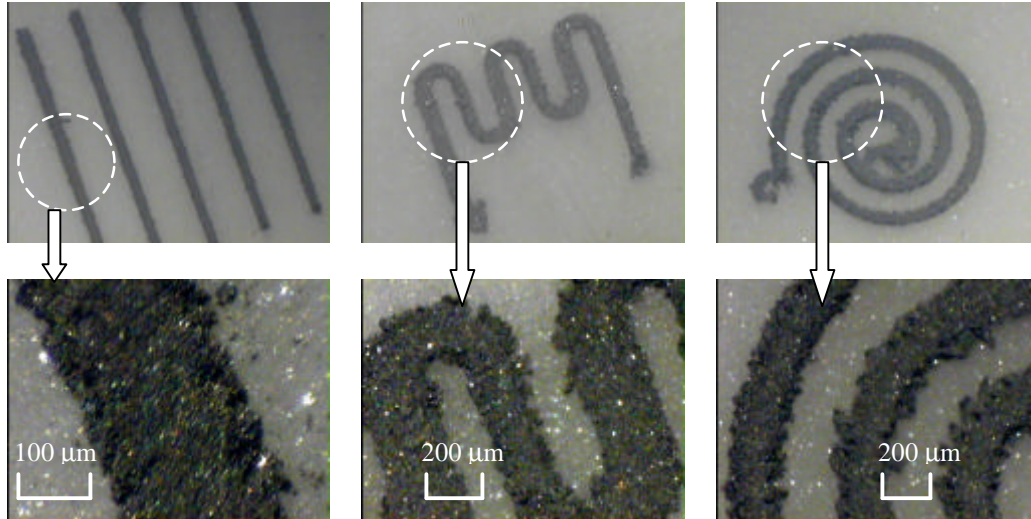

Fig.10. Patterns of stainless steel powders delivered by ultrasonic micro-powder feeding system

Numerous trials were performed on straight lines to obtain optimized parameters for high quality sintering of micro powder layers. Sintered spiral and wave lines, as shown in Figure 11, were achieved by ten paths of laser scanning at laser intensity of 0.497 J/cm^2, followed by multiple scanning paths at laser intensity of 0.746 J/cm^2. Blurs and extra un-sintered powders deteriorated quality of patterns. Laser micromachining or trimming of the sintered layers can be used to improve the quality of micro patterns.
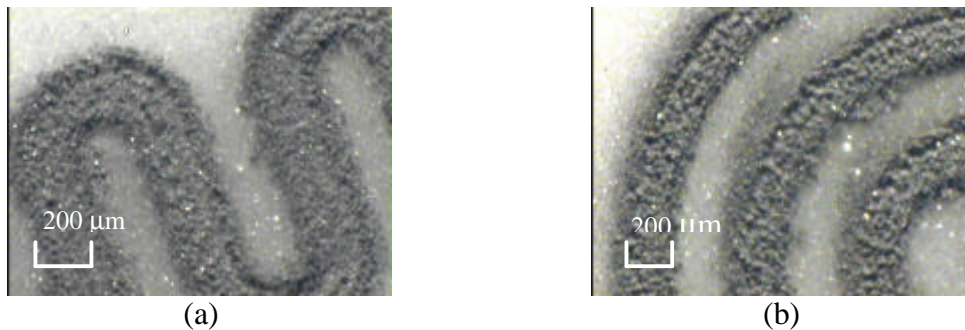

(a)   (b)

Fig.11. Patterns of sintered stainless steel powders
(a) 15 paths at the laser intensity of 0.746 J/cm^2 after 10 paths at 0.497 J/cm^2
(b) 41 paths at the laser intensity of 0.746 J/cm^2 after 10 paths at 0.497 J/cm^2

3.3. Integration of laser microdeposition and micromachining

The integration of the laser microdeposition and micromachining was studied on the stainless steel powder patterns. Laser beam with a wavelength of 355 nm was used. The diameter of its focused beam is set to 25.0 μm. From the characterization of laser micro-machining on UV laser beam of 355 nm, a low laser intensity of 2.55 J/cm^2 was used to avoid large debris and recast area. Several paths of laser micromachining were needed to trim the sintered patterns. Figure 12 shows images of a wave pattern before and after laser micromachining. The integration of laser microdeposition and micromachining produced clean and sharp edge for the deposited patterns, improving the resolution of manufacturing and thus quality of micro structures.
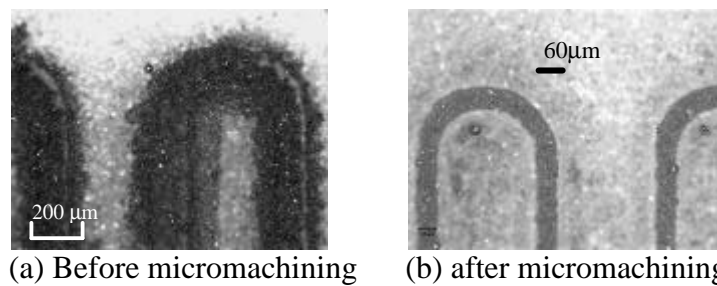

(a) Before micromachining   (b) after micromachining

Fig.12. Wave patterns before and after laser micromachining
(Laser intensity: 2.55 J/cm^2, laser machining speed: 0.5 mm/s)

4. Conclusion

This work presents a meso/micro manufacturing system that incorporates laser microdeposition and micromachining. An ultrasonic-based micro powder-feeding mechanism was developed and implemented to deposit micro powders through micro capillary tubes. Continuous discharge of micro powders was achieved at a flow rate of approximately 10^{-5}g per second.

Experimental study to characterize the micromachining and microdeposition has been conducted and initial results are presented. Laser micromachining was studied on stainless steel and copper with a Nd:YAG laser at wavelengths of 355 nm and 266 nm. The drilling depth is almost linearly proportional to the number of laser shots. A depth of as small as 0.1~0.4 μm can be obtained with a single laser pulse. Laser intensity significantly influenced the depth of machined holes. Laser microdeposition of copper and stainless steel patterns was accomplished by a Nd:YAG laser beam with the wavelength of 532 nm. Numerous trials were performed to obtain optimized parameters for high quality deposition of micro powder layers. Sintered layers with uniform and smooth shape were achieved.

The integration of laser microdeposition and micromachining produced clean and sharp edge for the deposited patterns, improving the resolution of manufacturing and thus quality of meso/micro structures.

5. Acknowledgements

6. References

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