Comparative analysis of microactuators fabricated by femtosecond and nanosecond laser micromachining

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Abstract. Laser micromachining technology is a cost-effective microfabrication technique for prototyping and in some cases batch production of miniature components and microdevices with complex geometries requiring high accuracy and precision. The objective of this paper is to analyze experimentally the effect of the laser micromachining process and its parameters, particularly, the pulse duration, on the characteristics of the fabricated functional microdevices. This was achieved through the microfabrication of two electro-thermally driven in-plane microactuators using a femtosecond and a nanosecond pulse laser. The dynamic/static performance of the microactuators was compared with respect to the required current/power and generated actuation force/displacement and the geometric quality of the machining.

1. Introduction

Laser material processing offers unique advantages over conventional machining and semiconductor technologies in precise and cost efficient prototyping and as well as volume production of miniature parts, functional components and microsystems from a wide range of materials, for example, optoelectronic, ultrahard and brittle materials. However, fundamental understanding of the laser-material interactions is essential for proper selection and optimization of a large number of interdependent process parameters related to the laser, optics, workpiece material and the motion system. The duration of the laser pulse is one of the most critical process parameters, which significantly influences the precision and surface quality of the laser machined parts. The physics of nanosecond (ns) and femtosecond (fs) laser ablation has been investigated extensively with several studies focussed on comparison of ns and fs laser micromachining [1-4]. Femtosecond pulse ablation frequently shows significant advantages over ns laser micromachining providing superior surface and cut quality, nano-scale material removal and negligible heat affected zone due to a combination of high energy density and short pulse duration eliminating the thermal effects. However, fs laser pulses may introduce significant mechanical stresses and amorphization in single crystal silicon [1].

In this paper, the effect of the ns and fs laser micromachining on the fabrication of a nickel-based microactuator was studied together with evaluation of the static/dynamic performance of the electro-thermally driven actuators. The actuators were fabricated using ns and fs laser micromachining with accuracy and precision within ±1 μm and the two laser approaches were compared in terms of the geometric quality, the required current/power and the generated actuation force/displacement.
2. Design
Figure 1 shows the design of the fabricated microactuator with four actuation units. The microactuator had a 2D symmetric monolithic structure consisting of a pair of identical, in-plane, cascaded structures linked together at the top with a horizontal beam as the motion platform. Each cascaded structure was formed by a serial connection of several actuation units, which magnify the output in-plane displacements. The driving electric potential was applied between the two fixed electric pads at the bottom of each cascaded structure. The actuation principle was based on the electro-thermal effect. When an electric current runs through the conductive structure of the microactuator, Joule heating generates thermal expansion of all the individual actuation units and thereby the entire monolithic structure. As a result of thermal expansion of the actuation units in cascaded structures, the motion platform moves forward producing in-plane displacements and force. The monolithic structure was chosen to provide a symmetrical distribution of the voltage, temperature and displacements along each vertical cascaded structure and the entire actuator. More detailed description of the design of similar microactuators can be found in [5,6].

![Figure 1. Schematic showing design of the fabricated microactuator.](image)

3. Microfabrication

3.1. Micromachining systems
Two micromachining systems with ns and fs lasers were used for microfabrication. The ns system was equipped with a Q-switched diode pumped solid state Nd:YAG laser operating at a wavelength of 355 nm with a pulse width of 20 ns and pulse-to-pulse energy stability of less than 5% rms up to 30 kHz for linear polarization in the TEM00 mode. The fs system was based on a Clark-MXR CPA 2010 laser, which delivers 150-fs pulses with wavelength centered around 775 nm with average power of 1 W corresponding to the maximum pulse energy of 1 mJ at a pulse repetition rate of 1 kHz. The laser beam was focused on to the workpiece surface by a combination of beam expander optics and a focusing objective. Both the laser and the three-axis CNC-based motion system were controlled and synchronized in time and space using in-house developed software, which enabled the setting up of the process parameters as well as the desired toolpath geometry. Laser micromachining of microactuators was performed with low fluence of 3.2 J/cm² for both ns and fs lasers, where the effect of the different laser wavelengths on laser-material removal process is minimal [3,4].

3.2. Results and analysis
Two microactuators were fabricated using ns and fs lasers with similar geometric accuracy of ± 1 µm from a Ni foil with a thickness of 25 µm having overall dimensions of 2220 (W) x 516 (L) µm and a width of the actuation beams of 10 µm (figure 1). The machining quality of the fabricated microactuators was analyzed through optical measurements and using a scanning electron microscope.

The SEM images in figure 2 shows the geometric quality of the machined actuation beams, the most critical design element related to the performance of the microactuator. As expected, the fabricated fs actuator was found to have a superior, clean quality cuts without burrs and with negligible heat affected zones. In comparison, the actuation beams of the ns actuator had rough side-
walls and significant amount of burrs and build-ups as a result of the ns laser-material interactions. During the ns laser material removal, burrs and build-ups in the sharp corners of the internal triangles were often re-adhered to the machined surface fusing the internal triangle to the rest of the structure. This effect was not observed in fs micromachining.

The fs micromachining created a different microfabrication issue based on the fact that fs laser pulses introduced significant mechanical stresses [1] into the material. The nickel foil used for microfabrication was hardened by cold rolling and therefore had built-in internal residual stresses. Therefore, the actuation beams became twisted and the entire structure was significantly deformed after fs microfabrication. The success rate was only 1 in 10 in the case of fs laser microfabrication of the microactuators. These deformations were not observed in ns microfabrication perhaps because the heat generated by the ns laser-material interactions caused internal stress relieving and annealing.

![Figure 2. SEM image showing geometric quality of the actuation beams for the fs (a) and ns (b) laser fabricated actuators.](image)

### 4. Performance testing

#### 4.1. Experimental set-up

The experimental setup for evaluating the performance of the fabricated microactuator consisted of a power supply (Agilent A3631A), 1Ω power resistor, digital oscilloscope (LeCroy WaveRunner, LT354), optical microscope (Olympus, SZX12) with a CMOS camera under Visual Gauge™ software control, and desktop computer. The microactuator was mounted on a small piece of glass glued to a plastic container and it was wired to a standard socket for electrical connections. Two channels of the oscilloscope were connected to the circuit to measure the applied voltage across the microactuator and the applied current across the power resistor. The performance evaluation involved switching of the power supply to apply voltage and current to the microactuator in discrete time steps, recording electrical signals with a digital oscilloscope, and using a camera and microscope to capture the synchronous planar displacements of the microactuator.

#### 4.2. Results and analysis

Major electro-mechanical characteristics such as generated displacement and force versus applied current, voltage and power, were studied in detail to characterize both, the static and the dynamic performance of the fabricated microactuators under constant current (0.60, 0.80, 0.10, 0.12, 0.14, 0.16 A) conditions. The experimental results, summarized in figure 3, show that both the ns and fs microactuators generate comparable displacements with a difference of ≤ 1 µm within the range of the applied currents. The ns and fs microactuators generated a maximal displacement of 8.2 µm and 9.2 µm, respectively, for 0.16 A current. The displacement was found to increase with increasing current in proportion to \( I^2 \). The current-voltage characteristic (figure 3) presents the change in the resistance of the microactuator due to the changes in the physical-mechanical properties of the material on
heating. For ambient conditions, ns and fs microactuators exhibited comparable resistances of 2.5 Ω and 2.8 Ω, respectively, for 0.06 A. However, heat generated at higher current of 0.16 A led to 3.1 Ω (1.24x increase) and to 5.9 Ω (2.12x increase) resistance for the ns and fs actuators, respectively. On average, the fs actuator exhibited 47.5% more resistance than the ns actuator. The current and the power were investigated as a function of the generated actuator force as shown in figure 4. The ns microactuator generated at least 10% more force than the fs actuator within a similar range of the applied currents. Also, the ns actuator required at least 45% less power than the fs actuator to generate similar force within the 50 – 800 µN range.

![Figure 3. Comparison of generated displacement and measured voltage as a function of applied current for both fs (FS) and ns (NS) actuators.](image)

![Figure 4. Applied current and power as a function of generated force.](image)

5. Summary

This paper presents a systematic study of the effect of the fs and ns laser micromachining on the dynamic electro-mechanical performance of the electro-thermally driven in-plane microactuator. The microactuator consisted of a 2D symmetric monolithic structure with four actuation units in each of two, cascaded structures having overall dimensions of 2220 (W) x 516 (L) µm and a width of the actuation beams of 10 µm. Two microactuators were fabricated using fs and ns lasers from a 25 µm thick pure Ni foil with a geometric accuracy of ± 1 µm. The performance of the actuators was experimentally evaluated at constant current. Each of the fs and the ns micromachining approaches presented different microfabrication challenges. Femtosecond microfabrication yielding only one working device in 10 samples due to the generation of internal stresses, while the ns microfabricated actuator were less precisely fabricated due to recast and coarse edge cuts. Nanosecond laser micromachining was shown to be preferable for the actuator microfabrication, which extends to monolithic functional microdevices and microsystems, despite the fact that the fs laser machined actuator had better geometric quality. In addition, the ns laser machined actuator exhibited better dynamic performance and lower power consumption.

References

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