Laser micromachining of the miniature functional mechanisms
Bordatchev, Evgueni V.; Nikumb, Suwas K.; Hsu, Wensyang

Publisher's version / Version de l'éditeur:
https://doi.org/10.1117/12.567518
Photonics North 2004: Photonic Applications in Astronomy, Biomedicine, Imaging, Materials Processing, and Education, pp. 579-588, 2004-12-09

Laser micromachining of the miniature functional mechanisms

Evgueni V. Bordatchev*[a], Suwas K. Nikumb[a], Wensyang Hsu[b]
[a]Integrated Manufacturing Technologies Institute, 800 Collip Circle, London ON, Canada N6G4X8
[b]Mech. Eng. Dept., National Chiao Tung Univ., 1001 Ta Hseuh Rd., Hsin Chu 300, Taiwan, ROC

ABSTRACT

The actual performance of a miniature mechanism significantly depends on the geometric quality of the machined part and specific features therein. To fabricate functional parts and features with accuracy and precision within +/- 1 μm or less, the laser micromachining system requires the capabilities of following the desired toolpath trajectories with minimum dynamic errors, high positional repeatability, and synchronization of laser firing events at precise time-and-location to ablate the material. The major objectives of this study are to fabricate miniature functional mechanisms using precision laser micromachining method, explore the machining challenges and evaluate the geometrical quality of the machined parts in terms of accuracy, precision and surface quality. Two functional mechanisms based on electro-thermal actuation have been studied. Several machining challenges related to the corner accuracy, the asynchronization of motions and, the laser-on/off events in space and time with respect to the part geometry have been addressed. The source of inaccuracies primarily stems from the geometric complexity of the mechanism that consists of several features, such as, arcs, radii, lines, curvatures, segments and pockets, along with their dimensional aspect ratio. Such a complex design requires a large number of inconsecutive trajectories to avoid thermal deformations. Copper and nickel foils with a thickness of 25 and 12.5 μm respectively were used in the fabrication of the prototypes. The machining challenges were successfully tackled and the geometrical performance of the fabricated prototypes was evaluated. Local feature accuracies within 0.1 - 0.2 μm have been recorded.

Keywords: laser micromachining, miniature functional mechanisms, microactuator, microgripper

1. INTRODUCTION

The successful development of miniature functional mechanisms, e.g., microactuators, microgrippers, micropumps *etc.*, depends on five interrelated components: area of application, principle of actuation, structure design, material to be used, and the fabrication method. Specific area of application mainly determines the choice of materials to be used, e.g., biomedical applications may require the use of biocompatible materials. However, the materials for the miniature mechanism need to satisfy the physical-mechanical properties to provide the desired functionality. In addition, the design constraints and the material characteristics may limit the fabricability of the part by the proposed fabrication method. Current engineering practices [1] have shown that bulk and silicon-based surface micromachining techniques are very efficient to fabricate the electro-static and electro-thermal driven micromechanisms due to good line width control and high compatibility with CMOS process. However, these technologies are not only suitable for other materials such as piezoelectric, metal, electroconductive polymers and shape memory alloys for part fabrication in the range of hundreds of microns but are also expensive. Laser micromachining on the other hand [2-5] is a cost-effective alternative technology due to its unique ability to machine a wide range of the light absorbing materials to fabricate miniature 2D/3D components with high degree of precision, surface quality and repeatability.

The performance of the miniature mechanism depends on the geometric quality of the machined components and the embedded geometrical features. To fabricate such components with feature accuracy and precision within +/- 1 μm or less, the laser micromachining system requires: a) optimization of process parameters related to laser, optics, workpiece material, and the motion system; b) perform the actual toolpath trajectory with minimum dynamic errors and high positional repeatability, and c) synchronize the laser material removal process at desired time-and-locations. This paper presents experimental results and our understanding during laser micromachining of miniature functional mechanisms. Several prototypes of electro-thermally driven microactuators and microgrippers were fabricated using ultra precision laser micromachining technology to explore the machining challenges. Also, the geometrical quality of the machined parts has been evaluated.

*evgueni.bordatchev@nrc-cnrc.gc.ca; phone 1 519 430-7107; fax 1 519 430-7064; http://imti-itfi.nrc-cnrc.gc.ca

2. LASER MICROMACHINING TECHNOLOGY AND SYSTEM DESCRIPTION

Laser micromachining technology incorporates a combination of material removal process, motion system and computer numerical control (CNC) [6,7]. Generally, two techniques have been intensively exploited – direct-write machining and the laser beam-scanning method. The difference in these techniques is in moving the workpiece in the case of direct-write machining as oppose to laser beam for the beam-scanning method. Direct-write micromachining system exploits the laser beam propagated in a Gaussian mode with low divergence, with very good beam profile, and focused to a small spot at a fixed precise position. 2D/3D components are produced by the CNC controlled, multi-axis motions of the workpiece. In case of the beam scanning technique, the laser beam scans with high speed over a workpiece using XY galvanometer mirrors, which are CNC controlled according to the desired tool path trajectory. Each technique has its own advantages and disadvantages, e.g., direct-write approach provides high accuracy and precision of fabricated components because of a very small focal spot; however, beam-scanning technique has significantly higher productivity due to high scanning speeds.

Recent technological developments are focused on new designs and control of the laser machining systems [8-10], incorporation of new generation of lasers with femtosecond and picosecond pulse duration [4,11-12], optimization of process parameters [2,5,13], and the process monitoring and control [14-17]. Optimization of process parameters is a most critical element for laser micromachining, because quantity and quality of laser material removal process depends on a variety process parameters related to laser, optics, workpiece material, and the motion system. As a result, there are no conventional procedures for selection of process parameters related to accuracy, precision and surface quality of the machined parts. Therefore, the operator selection of process parameters is primarily based on extensive experience and/or trial-and-error method. Furthermore, to achieve highest accuracy and precision on machined components the dynamics of laser-material interactions, dynamics of motions, and random variations within the laser beam parameters should be taken into account. When part and feature dimensions become particularly smaller (less than a few tens of microns), the thermo-dynamical processes within the laser-material interaction zone significantly influence the resultant part geometry, accuracy and precision [18].

In laser micromachining, generation of a crater by a single laser pulse is a starting point of the material removal process. After that, a set of dents produced by a series of laser pulses along the tool path trajectory creates a groove. Therefore, a 2D laser machined feature, e.g., laser cutting, is a set of one or several vertical grooves depending on the desired width. A set of horizontal grooves forms a layer, and therefore, 3D laser micromachining is a combination of one or several machined layers and, controlling the number of machined layers controls the machined depth. During the laser machining process, laser pulses are applied according to a prescribed toolpath for material removal. Each laser pulse removes a certain quantity of material and produces a crater in the workpiece material. The geometry and the volume of material removed depend on the material properties and the laser pulse characteristics. The relative location of two consecutive craters, generally known as an overlap, is also a process parameter considered for either 2D or 3D feature development. In ideal machining conditions the constant process parameters correspond to a deterministic concept of the laser precision machining when the desired (ideal) geometry of the machined part is a geometrical combination of dents with constant geometrical parameters (diameter, depth). The total volume of material removed depends on the selection of the frequency of the laser pulses and the travel speed for a given focal spot diameter, which is determined by the pulse energy, beam mode characteristics, and energy distribution. Experimental results [2,5,11,17-20] indicate that majority of process parameters are not constant and they have stochastic (random) components with certain statistical signatures. Random variations within the process parameters change the geometry of each crater and concomitantly change the final geometry of the machined part.

The laser micromachining system is a complex electro-optical-mechanical system consisting of the frame, laser, optics, motion system and process control software. Figure 1 shows the schematic of the laser micromachining system used for microfabrication of the microactuator and microgripper prototypes. Mechanically, the system was built on a granite bridge mounted on to a granite table to avoid environmental thermal-distortions and was placed on top of vibration isolation feet to avoid influence of any external vibrations. The system was equipped with a Q-switched diode pumped solid state Nd:YAG laser, which operates at a wavelength of 355 *nm* with pulse-to-pulse energy stability of less than 5% *rms* up to 30 *kHz* for linear polarization in the TEM00 mode. The beam delivery optical system was developed in-house to form and deliver the laser beam into the processing zone insuring Gaussian beam propagation. The laser beam was focused on to the workpiece surface by a combination of beam expander and a focusing objective. The three-axis

CNC-based motion system consisted of precision translation stages with linear motors for X and Y movements with a rated positioning accuracy in the order of 0.5 μm in the X- and Y-axis. Z-axes translation stage with ball-screw drive, having accuracy of 1 μm, was mounted vertically on the granite bridge. A vacuum fixture, located on the top of the XY translation stage, equipped with a fine control valve, designed to hold the sample foil flat and precisely at the focal point of the laser beam. Both the laser and the motion system were controlled and synchronized in time and space using an in-house developed software, which enabled the setting up of the process parameters as well as the desired toolpath geometry precisely. Foils of copper and nickel with thickness of 25 μm and 12.5 μm were used for the fabrication of the microactuator and the microgripper prototypes. An optical microscope "Olympus" (model PMG3) and the VisionGauge software were used to measure the geometry of the fabricated prototypes.

3. LASER MICROMACHINING OF A MICROACTUATOR

3.1. Design and geometry evaluation of a fabricated microactuator

Figure 2 shows the design of fabricated microactuator with eight actuation units. The design is based on multi-cascaded approach [21,22] and consists of pairs of identical, vertically oriented, cascaded actuation structures. Each actuation structure is formed by serial connection of several basic actuation units to magnify output vertical displacements. Each actuation unit is composed of two actuation beams and one constrainer. Each actuation beam is a V-shaped bent beam. Actuation structures are linked together by horizontal motion platform. Also, each actuation structure has fixed electric pad (anchor) to apply driving electric potential. The actuation principle is based on the electro-thermal effect. On application of electrical potential, the conductive structure of the microactuator produces Joule heating and thermal expansion of all the design elements and eventually the entire solid structure. Actuation beams expand and move up entire actuation unit with respect to the fixed anchors because of significant differences in the geometrical parameters, such as width and length, and therefore the electric resistance. Since the thin, long actuation beams dimensions are 10 μm x 25 μm (width to thickness) cross-section, they have higher electrical resistance, they heat up more than the wider constrainer with cross-section of 30 μm x 25 μm, and relatively lower electrical resistance. As a result, the actuation beam expands much more than the constrainer during the electro-thermal heating stage. When the actuation unit is electrically heated, actuation beam tends to expand in all directions evenly. However, the constrainer expands lesser than the actuation beam because there is no current flow through the constrainer that limits the heating and expansion of the actuation unit in the horizontal direction and it directs the primary displacements in the desired vertical direction. When electrical potential is applied between anchors to form a close loop, the output displacement and force are generated from the summation of all basic actuation units in one cascaded structure. The directions of motion can be outward (stretching mode) or inward (shrinking mode), depending on whether the actuation beams are under expansion or contraction. The symmetric monolithic structure was chosen to provide symmetrical distribution of voltage, temperature and displacements along each vertical cascaded structure. More detailed description of the similar microactuator with seven actuation units can be found in [22]. It is important to note that the design of the microactuator combines optimization possibilities to provide desired displacements by specific number of actuation units and desired force by a number of cascaded actuation structures.

A set of microactuators prototypes with one, three, seven, eight and ten actuation units was fabricated. Table 1 summarizes dimensional accuracy in terms of desired/machined dimensions, absolute and relative accuracy. A microactuator with overall dimensions of 2220.0 μm x 1409.0 μm has a complex design, and requires a large number of inconsecutive cuts to avoid thermal deformations. Therefore, overall dimensions have more significant errors, e.g. 2222.1 μm x 1413.2 μm (2.1 μm x 4.2 μm) due to accumulation of positional errors over a large number of motion steps. Contrarily, an accuracy of local elements (features) is very high, e.g. 10.0 μm vs 10.7 μm, 90.0 μm vs 90.6 μm, 50.0 μm vs 50.7 μm, 30.0 μm vs 30.5 μm. It is important to note that this study is a feasibility research only, and therefore it is mainly focused on resolving difficulties and overcoming challenges during laser micromachining process to obtain desired dimensions, accuracy and precision. To obtain better accuracy, tool path trajectory correction was also implemented during preparations.

3.2. Challenges in laser micromachining of a microactuator

In the fabrication of microactuator, there were two major challenges during laser processing – namely, the optimization of process parameters and the dynamic performance of the entire laser micromachining system due to the complexity of the geometrical design. Optimization of process parameters, such as, laser power and frequency, working distance, feederate *etc.* that directly affects the quality of the material removal process, size of the process-affected zone and cut quality. These aspects were not studied during the course of this work. Main focus of this study was to discover key limitations in the fabrication capability related to the geometrical complexity of the actuator design and corresponding system performance. Most significant challenges were related to

- accuracy of corners,
- asynchronization of laser-on/off events and motions in space and time with respect to the part geometry, and
- machining of sharp internal and external corners.

Typical examples of these challenges for the microactuator prototype are presented in Figure 3.

Dynamic performance of the motion system is a key element for achieving the highest accuracy and precision of parts from a particular laser micromachining system. In Figure 3a it can be seen that the corners are rounded because Y-movement started before the X-movement ended. Therefore, the accuracy of the corners depended on the proper tool path trajectory with respect to part geometry. Conventional CAD/CAM systems do not provide options to correct this issue. The solution consists in modification of a tool path trajectory with respect to blending options of a particular motion controller.

Modern motion controllers have advanced capabilities such as a "look-and-calculate ahead" feature. An improper use of this feature could cause asynchronization of laser-on/off events and motions with respect to part geometry thus leading to errors in the tool path trajectory and final part geometry, e.g. overcuts and undercuts. For example, in Figure 3b, laser is turned on before proper time and space location causing erroneous cutting of the part geometry. Again, the solution involves proper programming of the tool path trajectory and blending options to delay execution of a consecutive laser on/off action until motion is completed.

The design of microactuator involves two critical features – sharp corners: with 5° internal corner angle between actuation beam and the constrainer and a 10° external corner angle between two actuation beams as shown in Figure 3c and Figure 4. Fabrication of such complex 2D design as microactuator usually incorporates two stages – laser micromachining (primary operation) and removal of internally machined pieces (secondary operations), e.g. internal triangular pieces between actuation beam and constrainer. It is quite obvious that quality of laser material removal process will correspond to how easily internal pieces will come off after the machining process. Our experiments showed that the machined pieces, attached to the internal 10° corners, come off easily after laser machining and do not create a challenge for secondary operations. Contrarily, the triangular pieces remained inside adjoined to the adjacent walls for the 5° corner angles as shown on Figure 4 (left). This fabrication challenge was quite critical during machining of the entire microactuator. Increasing number of machining passes to loosen up the attached pieces – did not provide the desired results, because the width of cut and the surrounding affected zone significantly widened to cause actuation beam breakages. Detailed analysis to find solution for this challenge is shown in Figure 5. It was observed that, during laser micromachining of sharp corners, tool path trajectories located close to each other caused melting of the material inside internal corners and correspondingly fusing the internal triangle to rest of the structure. In addition, machining of such sharp corners will always have an error, because the laser beam could not be fitted into such a sharp corner (see Figure 5a, left). Fabrication of the sharp corner presented a critical challenge for motion system performance, because motions change direction at this point that requires deceleration and acceleration and therefore more material was removed (see Figure 5b, left). In order to resolve this issue, design of the sharp corner was modified. In the modified design, one side of the sharp corner was moved up 10 μm as shown in Figure 5a. This also enabled smooth velocity profile without fusing occurrences (see Figure 5b, right), clean corners (see Figure 5c, right), and even increased dynamic performance of the entire actuator by ~3.4 % (see Figure 5d).

3. LASER MICROMACHINING OF A MICROGRIPPER

3.1. Design and geometry evaluation of a microgripper

Microrobotics and microassembly technologies employed in the development of the micro-electro and micro-opto-electro-mechanical systems (MEMS/MOEMS), often require the use of a microgripper as an end grasping tool for assembly, handling/holding and manipulating micron-size objects such as, tiny mechanical parts, electrical components, biological cells, bacterium, *etc*, without damage or destruction. As a functional prototype for such applications, nickel-based microgripper prototype, shown in Figure 6, was developed. The microgripper design consists of a pair of identical multi-cascaded actuation structures (microactuators) oriented in a face-to-face direction to move normally open tweeze jaws towards each other acting as microtweezers. Tweeze jaws are supported by vertical levers with fixed ends to hold the object. Each microactuator consists of four actuation units joined horizontally in a consecutive order to build the cascaded structure and supported by a fixed pillar on the outer side. The actuators are electro-thermally driven and generate output tweezing displacement and the force via cumulative effect from the displacement and force generated from each individual actuation unit. Design of the actuation unit is similar to the design of a microactuator described in Section 2.1 and it consists of a geometrical combination of a constrainer and two semi-circular-shaped actuation beams. Due to the symmetrical structure of the actuation unit, there is no current flow through the constrainer and therefore, the constrainer expands less actuation beams that limits the expansion of the entire actuation unit in the vertical direction and directs the primary displacements in the desired horizontal (tweezing) direction. More detailed description of the similar microgripper with five actuation units can be found in [23]. Figure 6 shows the nickel-based microgripper prototype with overall dimensions of 1.4 (L) x 2.185 (W) *mm* fabricated by direct-writing laser micromachining technique. Table 2 summarizes the dimensional accuracy of the fabricated prototype in terms of desired/machined dimensions and absolute/relative accuracy. The average absolute accuracy of the fabricated prototype and its features was 1.74 μm. Note that some dimensions of the fabricated prototypes were machined within sub-micron accuracy, for example, the width of the tweezing jaws and the length of the constrainer represents feature accuracy of 0.5 μm and 0.1 μm respectively, mainly due to high positional accuracy of the motion system, proper synchronization of motions, laser on/off events and the desired geometry.

3.2. Challenges in laser micromachining of a microgripper

A key challenge in the fabrication of the microgripper prototype was the complexity of the microgripper design, which involves two issues. First issue deals with the high-aspect ratio (dimensional) between individual elements and the overall dimensions, which is 1:87 between the width of the actuation beam (25.7 μm) and the width of the entire microgripper (2.185 *mm*). Secondly, entire design is a combination of geometrical features with small dimensions, such as the width of the actuation beam (25.7 μm), the width of the constrainer (50 μm), the width of the tweezing jaw (50 μm), diameter of the actuation unit (200 μm), *etc*. These two issues cause agile motions during laser machining where dynamic loads and therefore, errors are maximal and motions are not smooth with non-uniform actual velocity due to sharp corners. For example, dimensions, such as, the width of the constrainer (52.7 μm), the outer diameter of the actuation unit (206.0 μm), the width of the actuation beam between two adjoining actuation units (21.7 μm) created by agile motions are not sufficiently accurate. In addition to large dynamic errors, agile motions break time/space synchronization of the laser on/off events with desired geometry and actual motions caused the over/undercuts due to poor dynamic performance of the motion system. Such agile situations, in which it is necessary to change the direction of motions abruptly, e.g. sharp corners, create significant dynamic positioning errors due to the inertia of relatively heavy XY translation stages. Accordingly the logic of CNC functioning, motion controller sends a signal to turn the laser on or off only after motion command executed. Therefore, dynamic overshoots of motions, can reach the magnitudes equivalent to the dimensions of local design elements (ex. actuation beam width), and become a part of the actual tool path trajectory. This breaks proper synchronization of motions, laser on/off events and the desired geometry. Figure 7 shows undercuts and overcuts during laser micromachining of the microgripper as results of asynchronization of the laser on/off events and agile motions when the laser is turned on ahead of the desired time and space location resulting in inaccurate machining. In addition, the laser by itself is an inertial opto-mechatronic system including a method to turn it on/off, e.g. by using an electro-mechanical relay, which requires additional on/off switching time that causes additional delays. Conventional CAD/CAM systems do not provide advanced options to correct this issue. In order to achieve higher level of accuracy and precision of the fabricated prototypes, this dynamic performance of agile motions was taken into account and desired tool path trajectory was corrected. In addition, to match the actual tool path trajectory and desired geometry, the blending options to delay/advance execution of consecutive laser on/off events until the motion was completed were implemented.

4. SUMMARY AND CONCLUSIONS

This work presents a systematic study of fabrication of miniature functional mechanisms using laser micromachining technology. In particular, the electro-thermally driven microactuator and the microgripper. The effect of complexity of the geometrical design on dynamic performance of the entire laser micromachining system, laser machining challenges and the geometrical quality of the machined parts for accuracy and precision were explored. Several machining challenges referred to the design complexity, high-aspect ratio (dimensional) between individual elements and the overall dimensions, corner accuracy, agile motions and asynchronization of motions and laser-on/off events in space and time with respect to the part geometry have been addressed. The machining challenges were successfully tackled and a set of microactuators prototypes with one, three, seven, eight and ten actuation units and one microgripper prototype with four actuation units were fabricated having local feature accuracies $< +/- 1\ \mu m$. Following conclusions can be drawn from these studies:

1. To improve the geometric quality and performance of the miniature functional mechanisms fabricated by laser micromachining technology, the dynamic performance of the entire micromachining system with respect to the design complexity and fabricability of the mechanism along with the local geometric features, such as, external and internal corners, non-consecutive cuts, *etc*, should be taken into account.
2. The design complexity of the mechanisms consisting of several geometrical features, such as, lines, arcs, radii, curvatures, corners, segments and pockets, and desired dimensional aspect ratio, incur challenges that stem from the agile motions and asynchronization of motions and laser-on/off events with respect to the part geometry and cause inaccuracies within the geometric features.
3. Tool path trajectory corrections with respect to motion dynamics and proper synchronization of motions and laser-on/off events are required to overcome challenges in laser micromachining of a mechanism with desired geometry, accuracy and precision.
4. The results enable high quality, precise fabrication of miniature functional mechanisms with complex 2D/3D geometry for MEMS/MOEMS, microrobotics and microassembly applications.

ACKNOWLEDGEMENTS

This work was conducted under the joint program between National Research Council of Canada and National Science Council of the Republic of China. Thanks are due to Mr. Mahmud-Ul Islam, Director, Production Technology Research, IMTI, for his continued support in this work. The authors also appreciate the assistance of their colleagues, Mr. Hugo Reshef, Mr. Craig Dinkel, and Mr. Marco Zeman for their help in assisting the laser micromachining work. This study was also partially supported by NSERC Discovery Grant R3440A01.

REFERENCES

1. Madou, M.J., Fundamentals of Microfabrication: The Science of Miniaturization, CRC Press, New York, NY, USA, 2002.
2. Chang, J.J., Warner, B.E., Dragon, E.P. and Martinez, M.W., "Precision micromachining with pulsed green lasers," J. of Laser Applications, 1998, Vol. 10, No. 6, pp. 285-291.
3. Braun, A. and Zimmer, K., "Fabrication of MEMS structures by laser machining", Proceedings of SPIE, Vol. 4236, 2001, pp. 213-221.
4. Bonse, J., Baudach, S., Krüger, J. and Kautek, W., "Femtosecond laser micromachining of technical materials", SPIE Proceedings, Vol. 4065, 2000, pp. 161-172.
5. Bordatchev, E.V. and Nikumb, S.K., "An Experimental Study and Statistical Analysis of the Effect of Laser Pulse Energy on the Geometric Quality during Laser Precision Machining", Machining Science and Technology: An International Journal, 2003, Vol. 7, No. 1, 2003, pp. 83-104.
6. Steen, W.M., Laser Material Processing, 2nd edition, Springer-Verlag, New York, NY, 1998.
7. LIA Handbook of Laser Materials Processing, Editor-in-Chief: J.F. Ready, LIA Press, Orlando, FL, USA, 2001.
8. Di Pietro, P. and Yao, Y.L., "Improving Laser Cutting Quality for Two-Dimensional Countoured Paths", ASME J of Manufacturing Science and Engineering, 1998, Vol. 120, pp. 590 – 599.
9. Xie, Q., Li, S., Xu, Z., Wu, H. and Yin, Q., "The vector spot compensation applied in a CNC system for laser cutting machine", 1999, SPIE Proc., Vol. 3862, pp. 337 – 341.
10. Bordatchev, E.V., "Ultra-Precision Laser Micromachining System Integrated with Piezoelectric Motion Stage", Proceedings of 2004 International Workshop on Advanced Manufacturing Technologies and Integrated Systems, Editors: J. Jiang and E. Bordatchev, 2-3 June 2004, London, Ontario, Canada, ISBN 0-662-37151-8, Paper # AMT2004-33.
11. Meunier, M., Fisette, B., Houle, A., Kabashin, A.V., Broude, S.V., Miller, P., "Processing of metals and semiconductors by a femtosecond laser-based Microfabrication system", SPIE Proceedings, Vol. 4978, 2003, pp.

169-179.
12. Tonshoff, H.K., Ostendorf, A., and Wnager, T., "Structuring silicon with femtosecond lasers", SPIE Proceedings, Vol. 4274, 2001, pp. 88-97.
13. Di Pietro, P., Yao, Y.L and Jeromin A., "Quality optimisation for laser machining under transient conditions", J of Materials Processing Technology, 2000, Vol. 97, pp. 158 – 167.
14. Fox, M.D.T., French, P., Peters, C., Hand, D.P., Jones, J.D.C., "Applications of optical sensing for laser cutting and drilling", Applied Optics, Vol. 41, No. 24, pp. 4988-4995.
15. Song, W.D., Hong, M.H., Lu, Y.F., Chong, T.C., "Laser cleaning of printed circuit boards", Applied-Surface-Science, 2003, Vol. 208-209, pp. 463-467.
16. Bordatchev, E.V. and Nikumb, S.K., "Informational Properties of Surface Acoustic Waves Generated by Laser-Material Interactions during Laser Precision Machining", Measurement Science and Technology Journal, June 2002, vol. 13, No. 6, pp. 836-845.
17. Bordatchev, E. V. and Nikumb, S.K., "Geometric Quality Analysis and Process Control for Ultra-Precision Laser Micromachining," Proceedings of the ASPE 16th Annual Meeting, November 10–15, 2001, Arlington, VA, USA, pp. 281-284.
18. Vatsya, S.R., Bordatchev, E.V. and Nikumb, S.K., "Geometrical Modeling of Surface Profile Formation during Laser Ablation of Materials", Journal of Applied Physics, Vol. 93, No. 12, 2003, pp. 9753-9759.
19. Liu, Q., Yamanaka, J., Haugen, H.K., and Weatherly, G.C., "Single- and multiple-pulse Femtosecond laser irradiation of iron, copper, and aluminum," Proceedings of the Opto-Canada: SPIE Regional Meeting on Optoelectronics, Photonics, and Imaging, 2002, SPIE Proceedings, Vol. TD01, pp. 27-29.
20. Yousef, B.F., Knopf, G.K., Bordatchev, E.V. and Nikumb, S.K., "Neural Network Modeling and Analysis of the Material Removal Process during Laser Machining", The International Journal of Advanced Manufacturing Technology, 2003, Vol. 22, pp. 41-53.
21. Hsu, C.-P., Tai, W.-C., and Hsu, W., "Design and Analysis of an Electro-Thermally Driven Long-Stretch Micro Drive with Cascaded Structure," Proceedings of the ASME International Mechanical Engineering Congress, November 17-22, 2002, New Orleans, Louisiana, USA, pp. 235 – 240.
22. Bordatchev, E.V., Nikumb, S.K., and Hsu, W.-S., "Fabrication of Long-Stretch Microdrive for MEMS Applications by Ultra Precision Laser Micromachining," Proceedings of the Canada-Taiwan Workshop on Advanced Manufacturing Technologies, September 23-24, 2002, London, Ontario, Canada, pp. 243 – 251.
23. Bordatchev E. V. and Nikumb S.K., "Microgripper: Design, Finite Element Analysis and Laser Microfabrication," Proceedings of the 1st International Conference on MEMS, NANO and Smart Systems (ICMENS), Editors: W. Badawy and W. Moussa, 20-24 July 2003, Banff, Alberta, Canada, pp. 308-313.

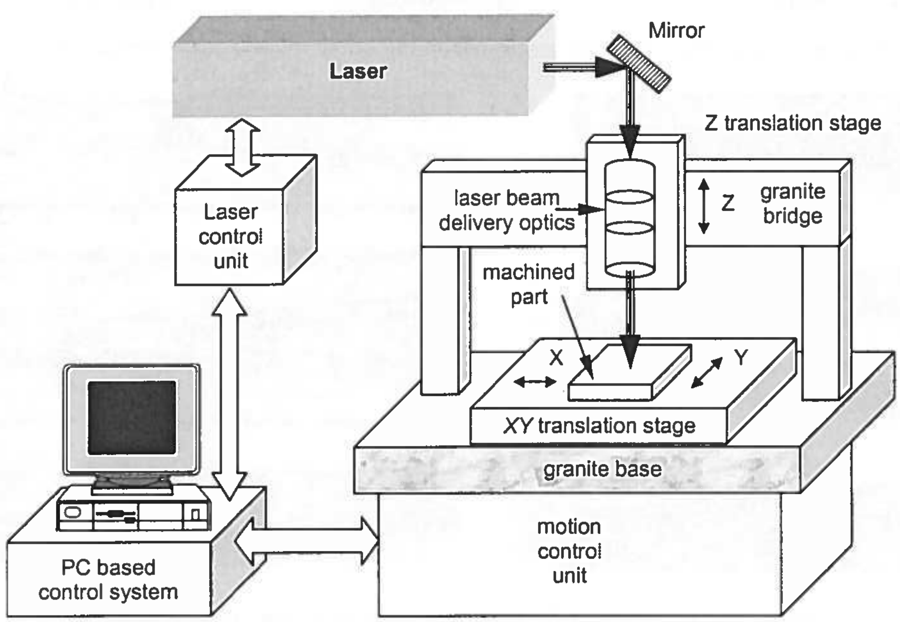


Figure 1. Schematic of the laser microfabrication system.

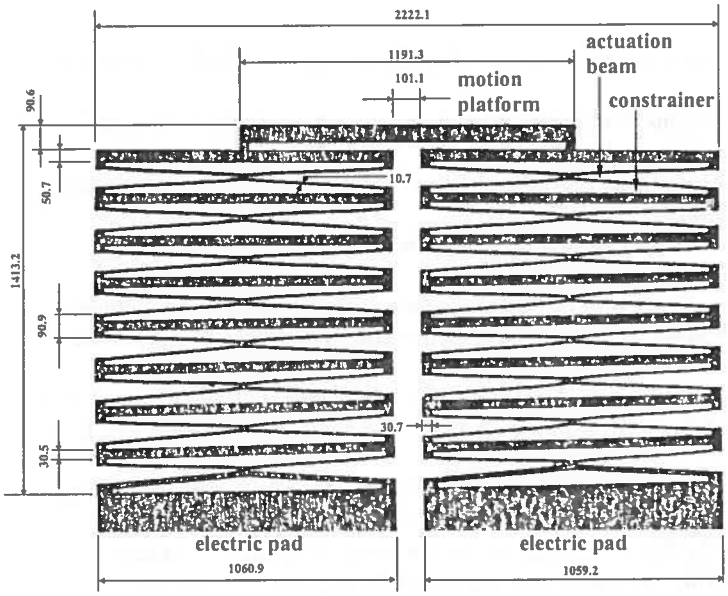
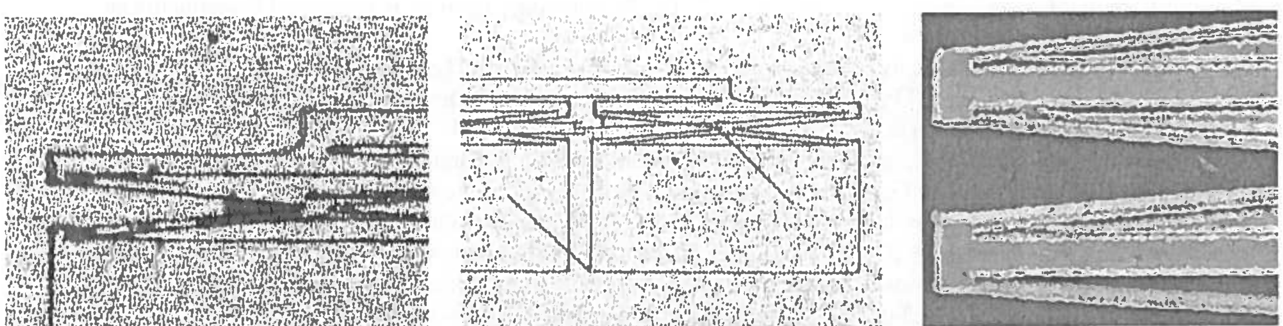


Figure 2. Fabricated nickel-based actuator prototype with eight actuation units (dimensions in μm).

Geometry evaluation — Table 1.

desired dimensions, μm	machined dimensions, μm	absolute accuracy, μm	relative accuracy, %
100.0	101.1	1.1	1.1
1190.0	1191.3	1.3	0.1
2220.0	2222.1	2.1	0.1
10.0	10.7	0.7	7.0
90.0	90.6	0.6	0.7
50.0	50.7	0.7	1.4
90.0	90.9	0.9	1.0
30.0	30.5	0.5	1.7
1060.0	1059.2	0.8	0.1
1060.0	1060.9	0.9	0.1
1409.0	1413.2	4.2	0.3
30.0	30.7	0.7	2.3



a) accuracy of corners b) asynchronization c) machining of sharp corners

Figure. 3. Challenges in laser micromachining of the microactuator prototype.

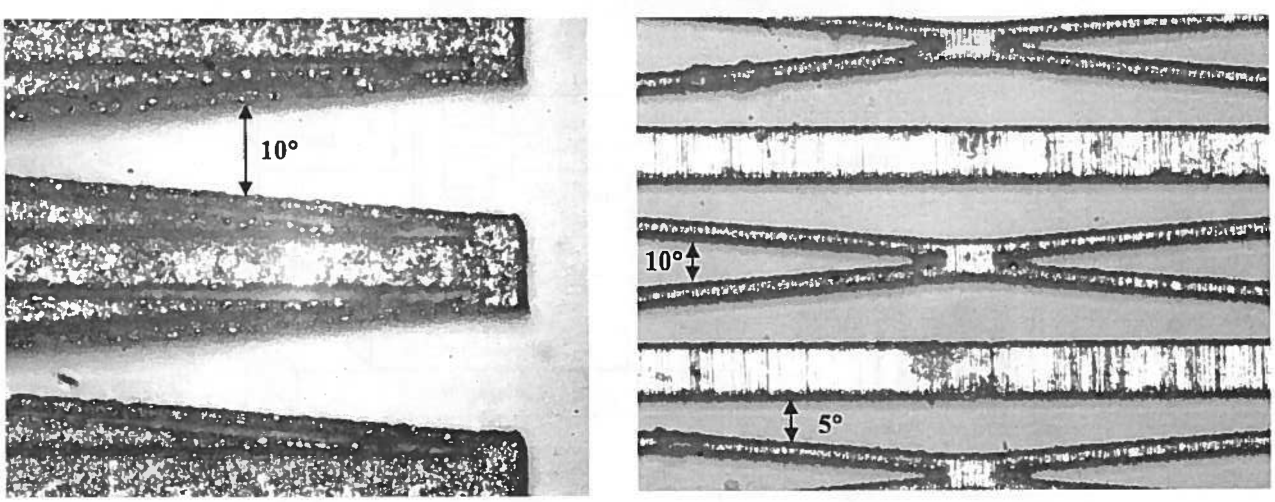
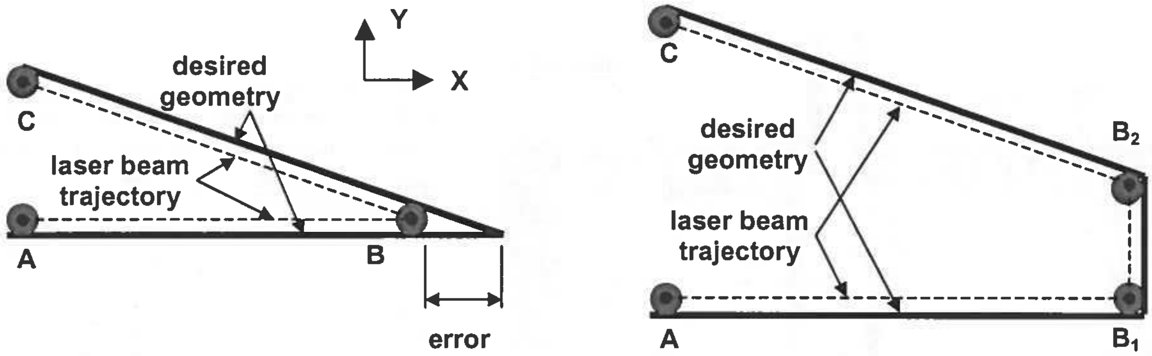
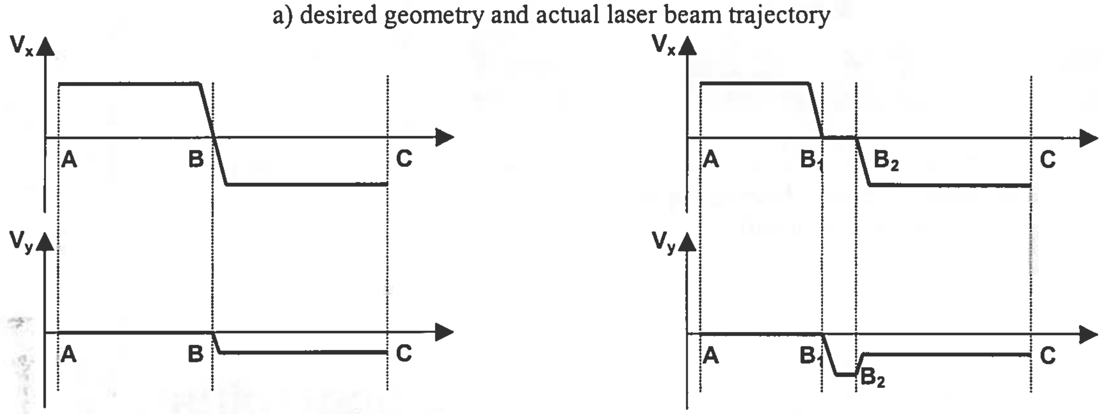


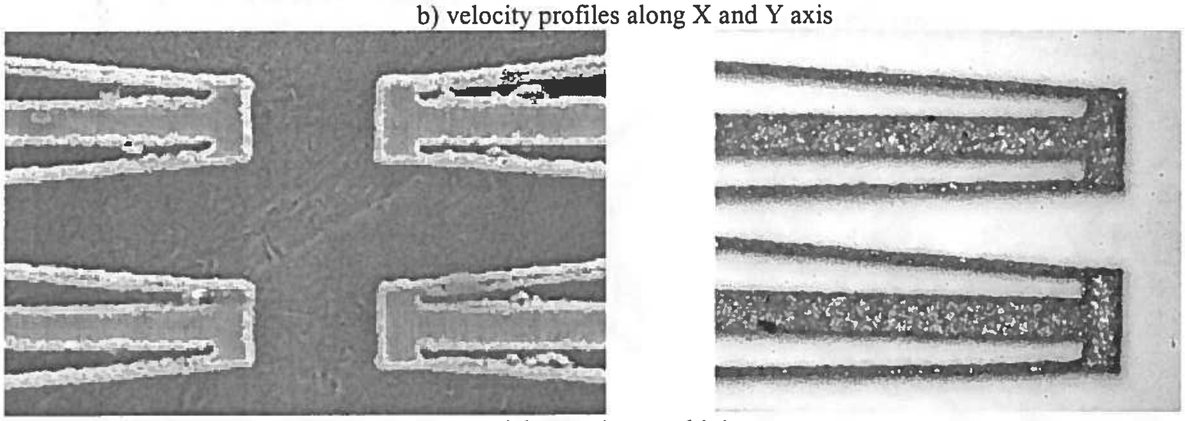
Figure 4. Comparison of laser microfabrication results of 5° and 10° internal sharp corners.

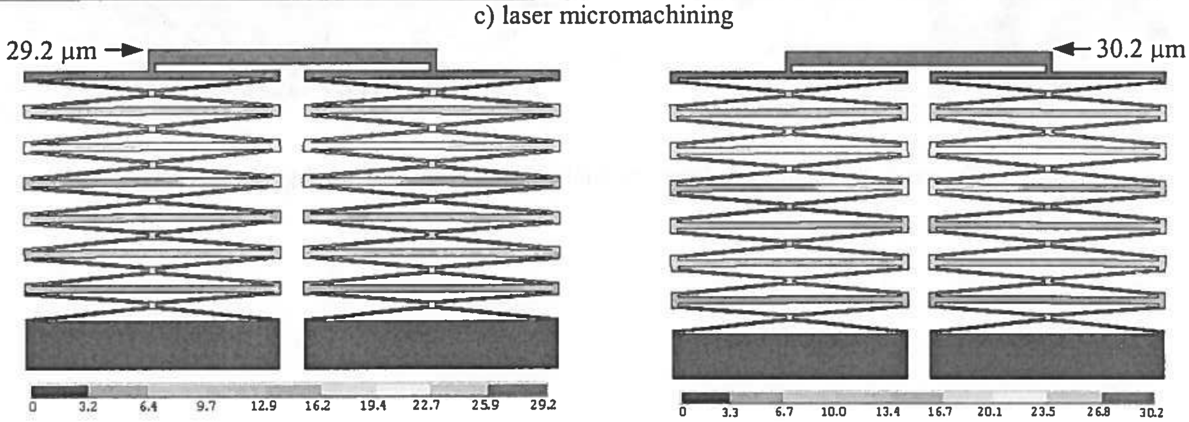


a) desired geometry and actual laser beam trajectory



b) velocity profiles along X and Y axis


c) laser micromachining



d) displacement distribution (in μm)

Figure 5. Comparison of original (left) and modified (right) sharp internal corners.

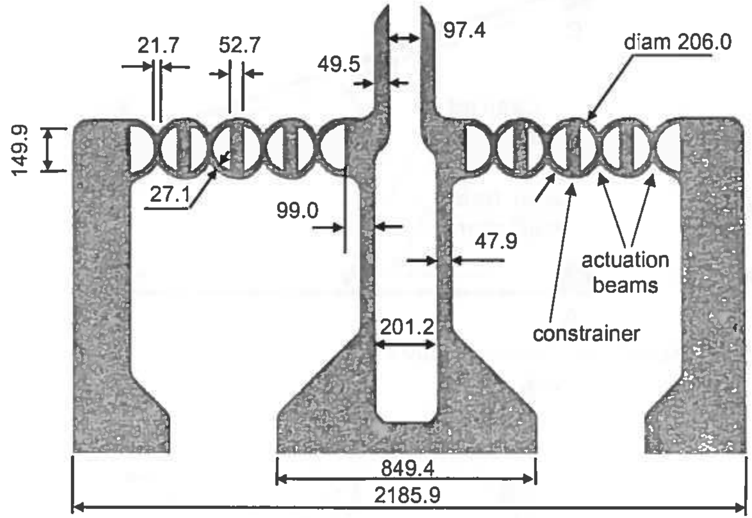


Figure 6. Fabricated nickel-based microgripper prototype (dimensions in μm).

Geometry evaluation Table 2.

desired dimensions, μm	machined dimensions, μm	absolute accuracy, μm	relative accuracy, %
25.7	27.1	1.4	5.45
50.0	47.9	2.1	4.20
50.0	52.7	2.7	5.40
50.0	49.5	0.5	1.00
100.0	97.4	2.6	2.60
150.0	149.9	0.1	0.07
200.0	206.0	6.0	3.00
200.0	201.2	1.2	0.60
850.0	849.4	0.6	0.07
2185.0	2185.9	0.9	0.04
100.0	99.0	1.0	1.00

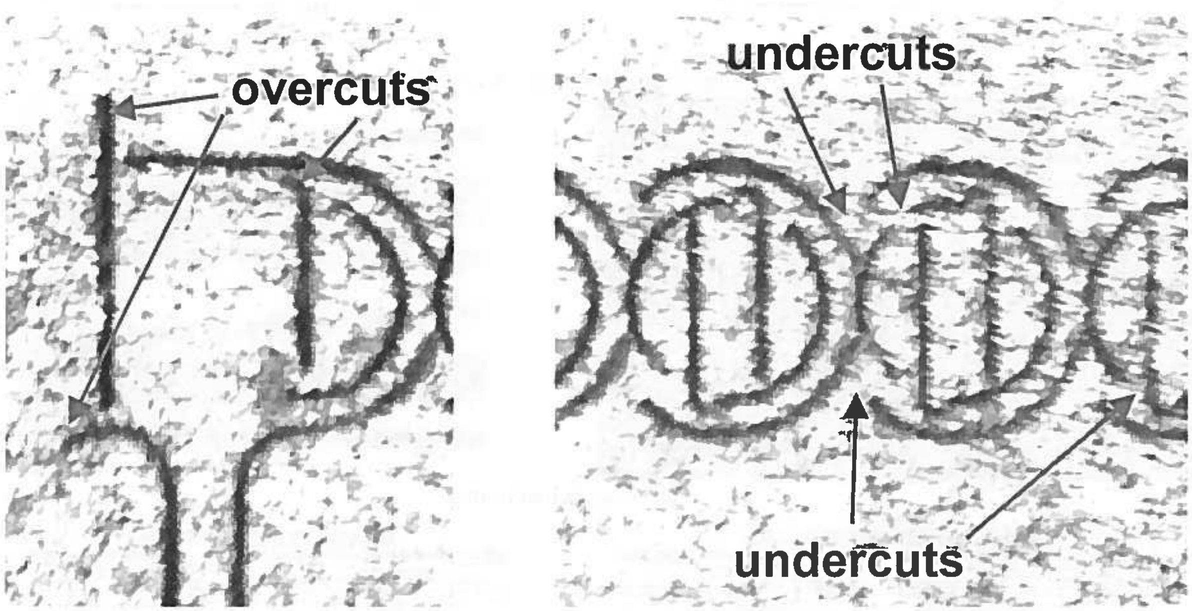


Figure. 7. Challenges in laser microfabrication of the microgripper.