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Review

MOCK-UP MACHINE FOR SUBTRACTIVE MANUFACTURING

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ABSTRACT

This article discusses the importance of development of equipment for subtractive manufacturing of microelectronics and micromechanics parts. The machine design for subtractive manufacturing of parts with nanometric procession is described. High precision subtractive manufacturing should be based on application of piezoelectric feed drives. It is established that the developed facilities should be equipped with systems of passive and active vibration insulation. The obtained experimental results confirm achievement of nanometric precision of manufacturing by the machine.

INTRODUCTION

At present instrumentation and engineering industries operate with increasing portion of parts with micro- and nanosized surfaces of various shapes with tight tolerances. Such parts are often characterized by complex multilayer heterogeneous structure, for instance, on the basis of glass-fiber laminates, containing filler layers on the basis corundum, polymer binders, metal films. Nano-laminate items are also included in this range of products.

Subtractive manufacturing is often applied in technologies of such parts (Mahalik, 2006; Shuangyan, 2014). Nowadays the microelectronics and micromechanics parts are manufactured by means of multiaxial engineering equipment with manufacturing error of about 1 µm. Further increase in equipment precision is limited by insufficient positioning precision of actuators, elastic and thermal deformations, as well as external vibrations transferred by foundation. Existing analogs of commercial equipment for extra precise subtractive manufacturing provide positioning precision of about 10 µm. However, the inherent drawbacks of such equipment are that high precision is achieved only upon travelling along one coordinate.

In order to perform subtractive manufacturing of parts with submicron precision it is required to develop and design a machine with sliding error of actuators not exceeding 100 nm.

DESIGNING

One of the most important aspects of machine designing is selection of its layout which will provide precision and required operation scope. Machine layout is the combination of actuators and parts of supporting system characterized by their number, types, positioning and ratios. Layout selection was based on all possible variants, the best variant was selected in terms of issues of subtractive manufacturing with nanometric positioning precision of actuators. While varying the layout structure and spatial positions of elements participating in shape formation it is possible to obtain several various layouts of one and the same machine.

The layout factors are as follows:

- Layout structure: combination of certain coupled elements (stationary and movable) executing spatial motion;
- Spatial positioning of layout elements (main junction planes, in particular);

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- Dimensions of layout elements (mainly their dimension ratios), influencing on rigidity ratios of layout elements along different axes;
- Coordinate distances between rigidity centers of junctions and load centers (cutting force, weight of elements), strongly influencing on transfer of forces and motions;
- Factors of junctions: types of movable junctions with different length ratios of movable and stationary parts.

The set of possible motions of 3D machine elements with regard to common 3D coordinates will be comprised of the following main possible members:

X -spindle movement along X axis;

Y -spindle movement along Y axis;

Z -spindle movement along Z axis;

$\overline{X}$ -frame movement along X axis;

$\overline{Y}$ -frame movement along Y axis;

$\overline{Z}$ -frame movement along Z axis.

Herewith, it should be considered that the machine spindle can rotate, this motion is denoted as. C Therefore, the set of all possible motions of the machine, which form the basis of machine layout variants, is as follows:

$MPE = \{X, Y, Z, \overline{X}, \overline{Y}, \overline{Z}, C\}$

In order to determine the most reasonable layout of the machine for subtractive manufacturing with nanometric precision all possible layout flowcharts were analyzed (Lomakin, *et al*., 2015). The machine layout described by $\{\overline{X}, \overline{Y}, \overline{Z}, C\}$ was determined as the most reasonable, it can be implemented with various feed drives and various actuators: milling and polishing spindles and so on. This layout is based on stationary spindle and moving frame elements.

In order to improve precision of mock-up manufacturing machine it is necessary to provide extra precious feed drive. This drive should allow for nanometric precision of preset spatial motion path along three axes by means of compensation of motion errors of main drive of coordinate table. Such precision can be provided by application of drive on the basis of piezoceramics (Robinson, 2006; Heui, 2001). Feed drive on the basis of piezoceramics should allow for nanometric precision and smooth run, low friction forces, good damping properties and be free from plays.

Q-545 piezoceramic linear stages (Physik Instrumente, Germany) can be applied as feed drive of mock-up machine for subtractive manufacturing. The Q-545 linear stages are intended for linear motion of items with the weight up to 1 kg with high precision. The Q-545 linear stages are based on PI Shift piezoelectric motor. The PI Shift motors are characterized by the following advantages:

- No limitations on motion range;

- Self-blocking upon power failure, no heat emission in waiting mode;

- Minimum noises upon motion;

- Holding force up to 10 N, maximum speed higher than 5 mm/s;

- Simple controls;

- Relatively low cost.

The PI Shift piezoelectric motors are based on stick-slip effect. The drive is based on piezoelectric actuator, one side of which is connected to preloaded frictional element. Saw-toothed signal is supplied from controller to piezoelectric actuator. With increase in pulse voltage the piezoelectric element slowly expands and moves guide member, since pushing force does not exceed static friction force between the guide member and the frictional element. Upon sharp voltage drop the piezoelectric actuator quickly shortens, the guide member remains at its position, since the force by the piezoelectric actuator exceeds kinetic friction, which leads to slipping. Comparison of pushing forces with kinetic friction force is stipulated by the fact that the guide member moves by inertia at the start of voltage drop.

Design features of linear stages impose some limitations on their possible applications. Thus, for instance, it is prohibited to apply lateral forces to linear stages. Piezoelectric PI Shift motors cannot operate continuously. Maximum time of continuous operation should not exceed 10 s, then the drive should be idle for approximately the same time. When such conditions are met upon operation at ambient temperature the piezoelectric drive can guarantee uninterrupted movement up to 2000 m. In addition, the PI Shift motors are equipped with self-blocking function, they do not emit heat in idle mode.

The Q-545.140 linear stages are equipped with linear encoder, which provides precision of recurrent on-directional positioning of 18 nm due to motion feedback. In order to provide motions along two axes (X and Y) the Q-545 linear stages can be combined without auxiliary mounting elements. Vertical mounting of Q-545 linear stages (movement along Z axis) is implemented by Q-145 mounting rack.

Rapid feed and retraction of part from tool are performed by Sb-01 nanometric guide member based on PM-20R piezoelectric motor and steel ball guide. The high-torque low-speed PM-20R precision piezoelectric reverse rotation motor is intended for generation of both continuous and single-step rotation modes as well as for precise angular positioning. When the motor is de-energized, it serves as position holder.

3D model of feed drive is illustrated in Fig. 1a. Simulation of static loading of feed drive on the basis of finite element method (Fig. 1b) revealed sufficiently high rigidity of the design.

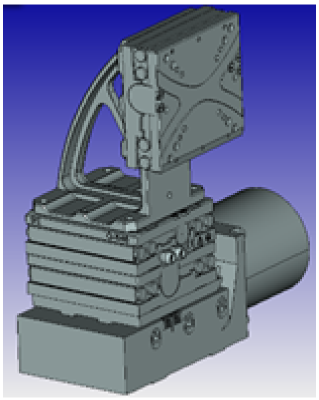
In order to estimate the expected machine precision, the mock-up feed drive was preliminary tested. The preliminary tests were performed without billets and machine actuators under PC control. Piezoelectric linear stage was tested without loading and under loads of 50, 100, and 150 g.

Consecutive stop positions were preset, achievement of these positions was controlled. Linear positioning error and repeatability were in accepted limits and did not exceed 10 nm. In the tests, complete controllability of the actuator was achieved upon sliding along three axes.

The mock-up piezoelectric actuator in the course of testing along three axes executed commands of linear and circular interpolation.

Interrelations between preset value and measurements by linear encoder for two test cases are illustrated in Fig. 2.

a)



b)

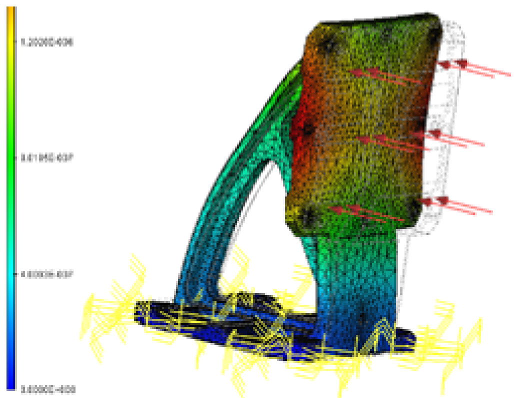
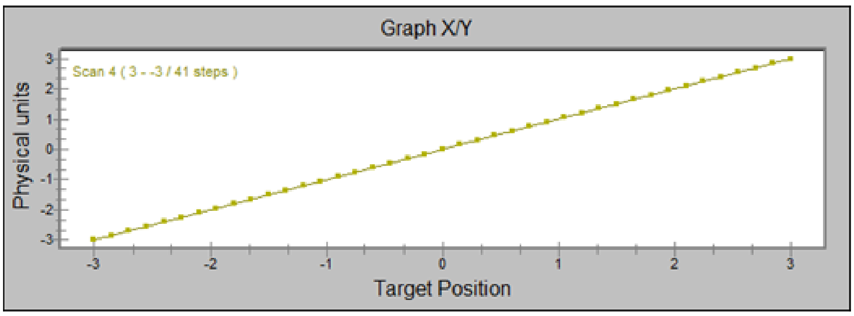


Fig. 1a and 1b 3D model of feed drive.



unloaded linear stage, sliding range from –3 mm to +3 mm with 0.15 mm increment.

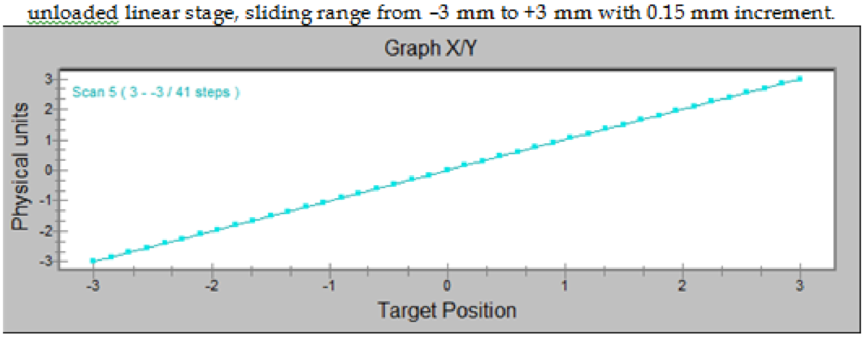


Fig. 2 Interrelation between preset sliding values and measurements.

Experimental results demonstrated that the developed feed drive provides positioning precision of about 10 nm.

Moderate dimensions of tool upon subtractive micro-manufacturing require for high precision of spindle rotation (up to 100000 min^{-1}). Such rotation speed should be based on electric spindles with water cooling and gasostatic bearings. Application of such spindles require for compressed air supply under pressure of at least 6 atm and water cooling. The tool cam be mounted by means of high precious sleeve, which can be locked by compressed air.

In order to protect against internal vibrations, the machine should be equipped with systems of passive and active vibration insulation (Collette, *et al.*, 2010; Hansen-Schmidt, *et al.*, 2014). The passive vibration insulation is aimed at maximum possible decrease in vibrations in order to promote operation of active vibration insulation. The active vibration insulation is aimed at damping of residual oscillations, which cannot be completely eliminated by the passive vibration insulation.

The passive vibration insulation of the mock-up machine is comprised of two solid granite plates installed on the table, elastic elements are inserted between the plates. Engineering components of the machine are installed in the upper plate.

The active vibration insulation of the mock-up machine is comprised of disc piezoelectric elements of variable length under the impact of electric voltage in opposition to external vibrations. The level of external vibrations is determined by accelerometers.

The mock-up machine is controlled by the developed system of computer numerical control on the basis of LPC2368FBD100 microcontroller with improved architecture ARM7TMDI, version S (Afonin, *et al.*, 2015).

Functional flowchart of mock-up machine for subtractive manufacturing is illustrated in Fig. 3. It is comprised of the following main components:

1. Process controller
2. Auxiliary function control unit
3. Cooling system
4. Active vibration insulation
5. Manual controls
6. Pneumatic system
7. Frequency converter
8. Spindle
9. Junction module for X axis
10. Precision piezoelectric drive of X axis
11. Junction module for Y axis
12. Precision piezoelectric drive of Y axis
13. Junction module for Z axis
14. Precision piezoelectric drive of Z axis
15. Control unit of auxiliary drive
16. Auxiliary drive of rapid feed

3D model of mock-up machine for subtractive manufacturing with vibration insulation system is illustrated in Fig. 4.

In accordance with the developed design and engineering specifications a mock-up machine for subtractive manufacturing with vibration insulation was fabricated (Fig. 5).

The mock-up machine was tested in accordance with predefined procedures, the tests confirmed achievement of specified properties upon meeting of engineering recommendations on modes of

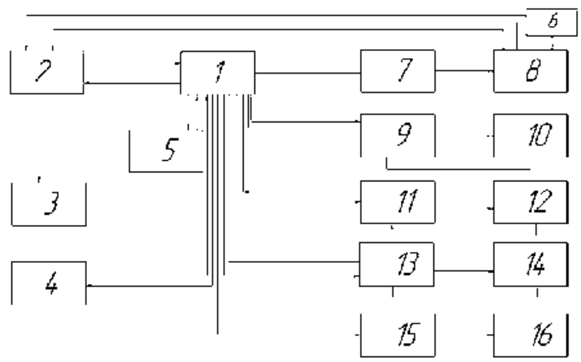


Fig. 3 Flowchart of mock-up machine for subtractive manufacturing.

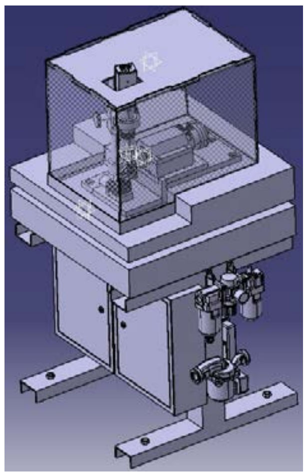


Fig. 4 3D model of mock-up machine for subtractive manufacturing with vibration insulation.

Fig. 5 Mock-up machine with complete vibration insulation.

subtractive manufacturing (Kirichek and Afonin, 2007; Lomakin and Afonin 2015; Afonin, *et al*., 2015a):

-Maximum sliding along three axes are at least 5 mm;

-Sliding error of actuators along X and Y axes does not exceed 100 nm;

-Coefficient of vibration transfer in the frequency range of 1 Hz to 200 Hz does not exceed 0.1.

CONCLUSIONS

Development of facilities for high precision subtractive manufacturing should be based on application of piezoelectric actuators. The developed facilities should be equipped with systems of passive and active vibration insulation. The mock-up machine for subtractive manufacturing was developed and fabricated after performed works.

Process variables of the machine upon fulfilling of engineering recommendations on modes of subtractive manufacturing correspond to specifications, hence, the machine can be used for manufacturing of microelectronics and micromechanics parts with nanometric precision.

CONFLICT OF INTEREST

We confirm that the presented data do not contain any conflict of interest.

ACKNOWLEDGMENTS

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REFERENCES

Afonin, A.N., Aleinikov, A.Y. and Gladyshev, A.R. 2015. Actuator control system of mechatronic devices with nanometric running precision. International conference proceedings. Urgent problems of robotic engineering and automatics. Belgorod. BGTU. 12-15.

Afonin, A.N., Lomakin, V.V., Aleynikov, A.Y. and Nikulin, I.S. 2015. Subtractive processing modeling by micromilling and microdrilling. *Int. J. Appl. Eng. Res*. 10 : 45232-45238.

Collette, C., Janssens, S. and Artoos, K. 2010. Active vibration isolation of high precision machines. *Diamond Light Source Proceedings*. 6(e1) : 1-5.

Hansen-Schmidt, J., Granchi, W. and Barth, T.M. 2014. Optimal vibration isolation for shock-sensitive machines. *Precis. Eng*. 206-210.

Heui, J.P. 2001. Ultra-precision positioning system for servo motor–piezo actuator using the dual servo loop and digital filter implementation. *Int. J. Mach. Tool. Manu*. 1 : 51-63.

Kirichek, A.V. and Afonin, A.N. 2007. Stress-strain state of the thread-milling tool and blank. *Russian Eng. Res*. 27 : 715-718.

Lomakin, V.V. and Afonin, A.N. 2015. Formal and software language means for specialized language implementation. *Int. J. App. Eng. Res*. 10 : 45239-45246.

Lomakin, V.V., Afonin, A.N. and Asadullaev, R.G. 2015. Adoption of solutions upon selection of design layout for subtractive manufacturing with nanometric precision. Scientific journal of Belgorod state university. *Econom. Informat*. 7 : 175-183.

Mahalik, N.P. 2006. Micromanufacturing and Nanotechnology. *Berlin: Springer-Verlag*. 477.

Robinson, S. 2006. Driving piezoelectric actuators. *Power Electron. Technol*. 4 : 40-44.

Shuangyan, L. 2014. Process planning for the subtractive rapid manufacturing of heterogeneous materials: Applications for automated bone implant manufacturing. PhD Thesis. Iowa State University, Iowa. 124.es Publ. 3 : 1-7.