Jurnal Teknologi

Full paper

The Investigation of a Micro-Component Machined on a Custom-built Miniature Machine Tool

Syaimak Abdul Shukor [a]*

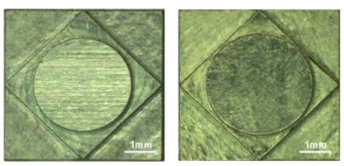
[a]School of Information Technology, Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor

*Corresponding author: syaimak@ftsm.ukm.my

Article history

Received : 29 March 2012
Received in revised form : 19 June 2012
Accepted : 30 October 2012

Graphical abstract



Abstract

Custom-built Miniature Machine Tools (MMTs) are now becoming more popular with the demand for reduced energy consumption and workshop floor when machining small/medium batch size micro-components. This paper investigates the capability of a custom-built 4-axis MMT through machining an "adapted standard' of micro-testpiece. The experiments have been carried out in two different materials: Carbon Steel (AISI 1040) and Titanium Alloyed (TiAl6V4) using solid carbide flat end mill cutters with 0.6mm diameter. From here, the surface quality and geometrical accuracy of the machined testpiece are evaluated and analysed. The investigation has shown that acceptable geometrical accuracies and surface quality of the machined micro-parts can be achieved using the in-house developed MMT. These results show that the use of the custom-made MMT does not hinder the micro-milling process to produce a good and satisfactory surface quality (R_a=0.04-0.07μm) and acceptable geometrical accuracy.

Keywords: Micro-milling; custom-built miniature machine tool; micro-testpiece

Abstract

Pembangunan *Miniature Machine Tools* (MMT) yang dibina secara sendiri semakin popular dengan meningkatnya permintaan terhadap pemesinan yang menggunakan tenaga yang berkurangan serta kapasiti lantai kerja yang sedikit apabila memesin komponen-komponen bersaiz mikro pada kadar pengeluaran yang kecil atau sederhana. Kertas ini mengkaji keupayaan satu MMT yang dibina sendiri yang mempunyai 4 paksi pergerakan melalui pemesinan satu bahan kerja bersaiz mikro (disesuaikan berdasarkan kepada piawaian pengujian pemesinan). Eksperimen telah dijalankan menggunakan dua bahan yang berbeza iaitu Carbon Steel (AISI 1040) dan Titanium Alloyed (TiAl6V4) serta mata alat karbida kisa hujung mata pemotong berdiameter 0.6mm. Daripada ini, kualiti permukaan dan ketepatan geometri bahan kerja tersebut dinilai dan dianalisis. Hasil kajian menunjukkan bahawa pemesinan menggunakan MMT yang dibina sendiri telah menunjukkan yang kualiti permukaan dan ketepatan geometri bahan kerja tersebut boleh diterima. Ini membuktikan bahawa MMT yang dibina sendiri tidak menghalang proses pemesinan pengisaran-mikro untuk menghasilkan permukaan yang berkualiti baik dan memuaskan (Ra=0.04-0.07μm) serta mempunyai ketepatan geometri yang dapat diterima.

Kata kunci: Pengisaran mikro, miniatur perkakas pemesinan-bina khas; bahan kerja bersaiz mikro

1.0 INTRODUCTION

As product development technology becomes more advanced, the size of produced devices decreases and this is where micro-products came into view. The use of micro-products has been rapidly increased through the past decade and the product development and design on new micro-products is likely to become the core competences of the specialist companies [1]. The increasing demands of micro-products such as sensors, lenses, surgery devices, gear and actuators in various industries such as Information Technology (IT), aerospace, medical and biomedical, automotive, telecommunication and electronic industries have geared up the development of specific micro-manufacturing processes and technologies [1, 2]. Although manufacturing such miniature features and components can be achieved on large-scale Precision Machine Tools (PMTs), design and construction of Miniature Machine Tools (MMTs) is acquiring great interest due to the recent advancements in Micro-Electro Mechanical Systems (MEMSs). In this context, micro-machining has become a popular technology of manufacturing where the tolerances, features and even part sizes are at the micro-scale level.

According to Hansen *et al*. [3], among the advantages of MMTs are the decrease of heat deformation of machine tools with subsequent reduction of their sizes, decrease of material consumption for machine tool construction (more expensive material with better properties can be used), decrease of vibration amplitudes and decrease in space and energy consumption.

In-line with the above positive progress, issues and advantages of the MMTs, the MCM research group at the University of Nottingham has developed an in-house 4-axis Miniature Machine Tool. As there are no guidelines, standards or manual to refer to in operating the MMT, the need to evaluate and assess the capability and performance of the MMT becomes an essential aspect. In reviewing the literature related to the custom-made MMT, it was found out that in order to assess the capability of the machine tool, the surface quality and the geometrical accuracy of the machined part were selected to be the main evaluation criteria [4, 5]. Various tool and workpiece materials were utilized in machining parts using in-house developed MMTs and the results indicate their capabilities to produce surfaces of acceptable quality and geometrical accuracy. The main objective of this paper is to discuss the results of the experimental procedures employed to evaluate the capability of the developed in-house 4-axis Miniature Machine Tool.

1.1 The in-house 4-axis Miniature Machine Tool (MMT)

Figure 1 shows the complete MMT (with cover of the machine has been removed) which has been set-up in a micro-machine lab, University of Nottingham.

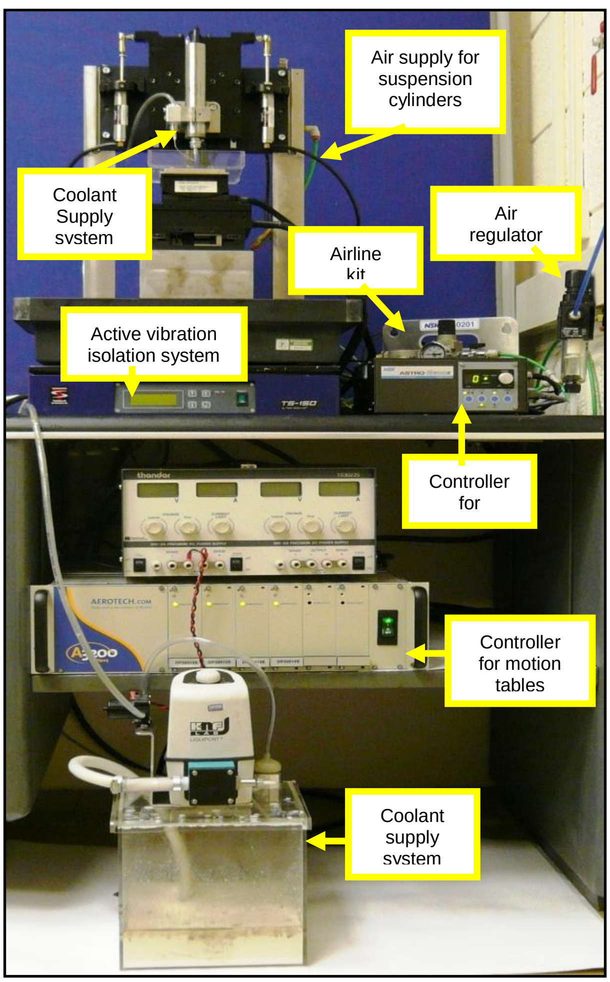


Figure 1 The set-up of the miniature machine tool

1.1.1 MMT Components

In the development of the MMT, a gantry configuration has been adopted for construction of the system in order to allow easy access to the working space and to exploit the advantages offered by the new-technology miniature weight compensated linear stages. Details on the major components of the MMT are described as the following:

1.1.2 Machine Tool Frame

The frame was manufactured of INVAR 36 alloy (INVARiable Ni -36%, Fe-63%) that was particularly chosen due to its low thermal expansion coefficient (1.3x10-6 °C-1 between 20-100°C), thus minimising the dimensional errors due to temperature variations.

1.1.3 Machine Base

The gantry frame was mounted on a granite base that with its low thermal expansion coefficient (8.6x10-6 °C-1 between 20-100°C) not only minimises the effect of temperature variation on the dimensional chain of the MMT system but also has, to some extent, the capability to damp external vibrations (140-1600Hz) [6].

1.1.4 Positioning Tables

The realisation of the 4-axis of MMT has been achieved by employing high resolution positioning stages (manufactured by Aerotech). Two linear motor stages (ALS130-025) assembled perpendicular to each other provide 25mm travel in X and Y directions. The direct drive goniometre (ANT-20G-90) placed on top of linear stages enables swivel (rotary) action of 20° in U direction. In addition, the vertical movement of 25mm in Z direction is 101 achieved using a dual counter-balanced linear motor stage (ALS130-025) that is fed by regulated dry air for suspension inside the cylinders at both ends to ensure smooth and stable operation of the stage.

1.1.5 Motor and Spindle Unit

A brushless motor-spindle unit with controller and airline kit (ASTRO-E500Z) was chosen. Brushless motor-spindle unit with ceramic bearings (EMS-3057) is an integrated motor and spindle solution with high speed rotation of 50,000rpm and low tool run-outs (<1μm). The controller (NE147) enables high degree of control over the speed while the airline kit (AL-0201) supplies dry and regulated air into the spindle. The spindle unit was attached to the dual counter-balanced head via the spindle arm that was manufactured of INVAR 36.

1.1.6 Cooling System

The cooling system designed for the MMT which consists of two sections: the suction/pumping system and the plastic container able to allow wet machining condition to be run in the MMT. The suction/pumping system functions are to deliver and to pump out the cooling liquid from the machining area and also to filter the coolant. The plastic container which comprises of two parts (the tray cover and the working tray) takes the role in protecting the motion tables. The coolant that will be used in this study is Hocut 3380 high lubricity chlorine and 103 sulphur free soluble oil blended with severely refined mineral oils. The resultant rich milky emulsion is very low foaming and suitable for high pressure coolant systems which associated with modern CNC machine tools. It was recommended to use between 4% and 6% concentration for general machining [7].

1.1.7 *Active Vibration Isolation System*

To ensure high degree of insulation of the working environment from the external sources of vibrations, an active vibration isolation system (TS-150) has been used as a dedicated table for the MMT. The active vibration isolation table has been placed under the granite base of the micro-machining system.

2.0 EXPERIMENTAL SET UP

In order to assess the cutting accuracy of the MMT, an 'adapted standard' micro-testpiece which is similar to the one suggested in ISO 10791-7:1998 (Test conditions for machining centres- Part 7: Accuracy of a finished testpiece) has been selected [8]. For the purpose of assessing the capability of the MMT, the defined standard micro-testpiece was scaled down appropriately as shown in Figure 2. It carries all the significant features of the machining standard and would be an appropriate example for assessing cutting accuracy of the MMT. Some of the significant features are:

- Circularity with the inner circle.
- Linearity or straightness of the outer square.
- Perpendicularity at the corners.
- Angular accuracy (45° at the edge of the inner diamond with outer square).
- Parallelism with the opposite sides of a square.

In this study, the 'adapted-standard' micro-testpiece was generated in two different materials which were the AISI 1040 and TiAl6V4. The milling process of the micro-testpiece was based on the recommended machining parameters from the tools manufacturers. The cutting tool used was Ø=0.6mm end mill from Sandvik Coromant (R216.32-00630-AE06G 1620 Coromill Plura). On completion of machining the micro-testpiece, the workpieces were evaluated for their geometrical accuracy and surface quality.

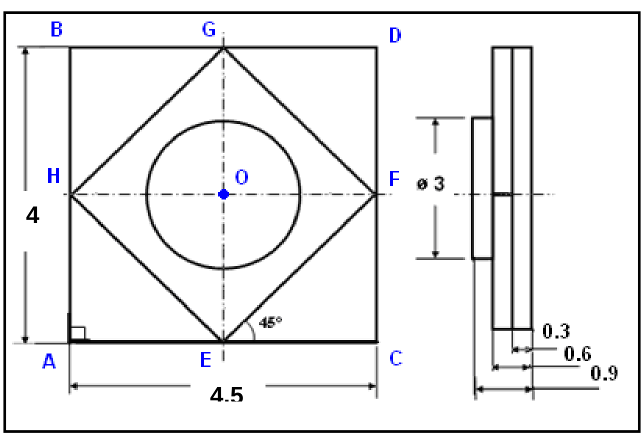


Figure 2 The 'adapted-standard' micro-testpiece (in mm)

The objective of machining the 'adapted-standard' micro-testpiece was to assess the capability of the MMT in term of surface quality and geometrical accuracy. The surface quality was assessed using surface profile analysis (e.g. R_a and R_z), while the geometrical accuracy was obtained via Keyence VHX-Optical Digital Microscope.

2.1 Machining Procedures and Parameters

In machining the micro-testpiece, each of the main features (cylinder, diamond shape and also the outer square) were generated by implementing the *contouring* function from MasterCAM at respective depths for each layer. The steps taken in machining the micro-testpiece are described below:

- First, the cylinder was generated and Figure 3 shows the layout of the milling operation using the machining parameters shown in Table 1 in a wet condition (coolant=Hocut 3380).

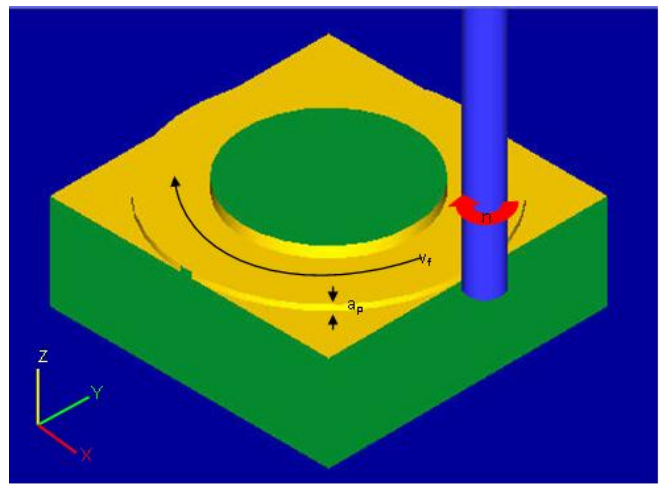


Figure 3 Layout of the cylinder machining operation

- After completing the machining of the cylinder, a diamond shape was then milled based on the layout shown in Figure 4.

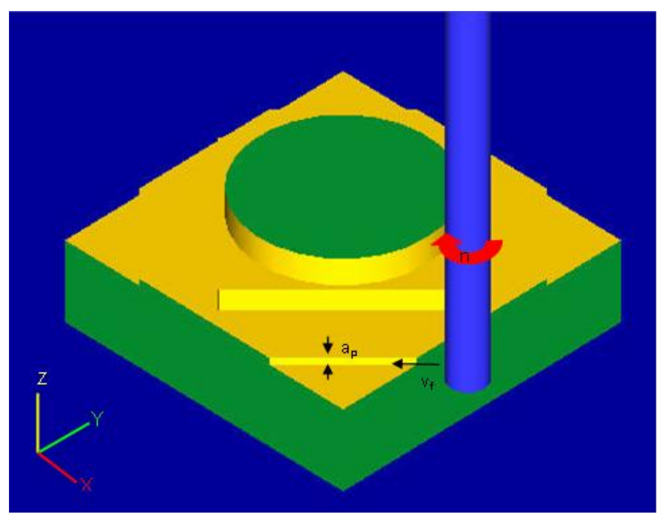


Figure 4 Layout of the diamond shape feature machining operation

- Finally, the outer square of the micro-testpiece was then machined via the layout illustrated in Figure 5.

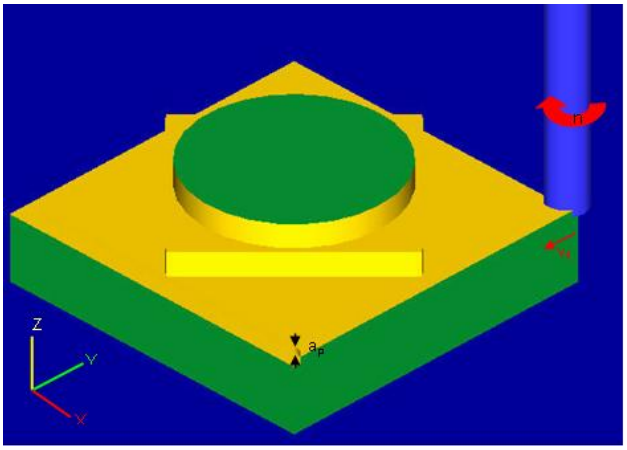


Figure 5 Layout of the outer square machining operation

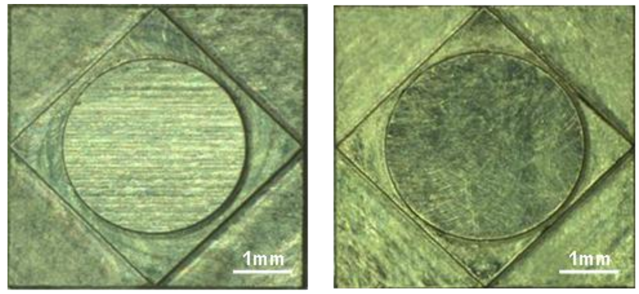
In this study, the 'adapted-standard' micro-testpiece was generated in two different materials which were the AISI 1040 and TiAl6V4. The milling process of the micro-testpiece was based on the recommended machining parameters from the tools manufacturers and also as suggested in previous study related to micro-milling [9-13].

Table 1 Machining parameters in generating micro-testpiece

Parameters	**Material**	
	AISI 1040	**TiAl6V4**
n (rpm)	50000	48000
$\mathbf{f_z}$ (mm)	0.011	0.010
$\mathbf{a_p}$ (mm)	0.03	0.03
$\mathbf{a_e}$ (mm)	0.03	0.03
$\mathbf{V_f}$ (mm/min)	1100	960
$\mathbf{V_c}$ (m/min)	94	90

■3.0 RESULTS

In Figure 6, optical images of the machined micro-testpieces ((a) – AISI 1040 and (b) – TiAl6V4) at x50 magnification from a Keyence VHX-Optical Digital Microscope are shown. From here, by observing the "as-machined" surfaces, it shows that no major defects (e.g. scratches) were found while the geometry looked clearly defined. In-depth analysis to investigate the significant features such as circularity with the inner circle, linearity or straightness of the outer square, perpendicularity at the corners, angular accuracy and parallelism with the opposite sides of a square the machined micro-testpieces were further evaluated the Keyence VHX-Optical Digital Microscope. While the surface quality analysis was carried out using a Taylor Hobson Talysurf CLI 1000.



(a) AISI 1040 (b) TiAl6V4

Figure 6 Machined micro-testpieces

Table 2 shows the result of the measurement made based on the aspects such as diameter of the cylinder, perpendicularity at the corners, FEC angle (45° at the edge of the inner diamond with outer square) and the dimension of AB, CD, AC and BD. For each measurement, the average value was presented together with the calculated standard deviation (3σ - 99% of confidence interval).

From these results, it can be noted that satisfactory geometrical accuracies of micro-components can be achieved using the particular MMT. Based on these results, it can be noted that the achieved dimensions deviated from their original by less than 5%. It can be concluded that acceptable geometrical accuracies of micro-parts can be achieved using the in-house developed MMT.

Table 2 Results from the microscope analysis on TiAl6V4 and AISI 1040

Aspect	**TiAl6V4**	**AISI 1040**
$\varnothing_{Cylinder}$ (mm)	3.1047 ± 0.0062	3.0542 ± 0.0045
$\angle FEC$ (degree)	45.0225 ± 0.5314	45.2875±0.4806
$\angle A$ (degree)	90.4433 ± 0.7677	90.2275±0.3265
$\angle B$ (degree)	89.9833 ± 0.6169	90.7825±0.2037
$\angle C$ (degree)	89.6267 ± 0.1644	90.2400±0.3309
$\angle D$ (degree)	90.0100 ± 0.3119	90.2025±0.1782
$\|AB\|$ (mm)	4.5068 ± 0.0095	4.4958±0.0062
$\|CD\|$ (mm)	4.4894 ± 0.0030	4.5045±0.0063
$\|AC\|$ (mm)	4.5221 ± 0.0064	4.5106±0.0074
$\|BD\|$ (mm)	4.5154 ± 0.0217	4.5010±0.0065

The surface roughness of the machined micro-testpieces was measured over a sampling length of 0.8mm and a cut-off length of 0.04mm using Taylor Hobson Talysurf CLI 1000. The measured R_a values varied between 0.04-0.07μm with higher values related to the surfaces generated towards the end of tool path (length cut of 129mm, machining time: approximately 42 min). By comparing the results above with the previous study in producing micro-parts, it can be concluded that the MMT is capable to produce an acceptable value of R_a (0.04-0.07μm) and R_z (0.23-0.31μm) based on the recommended machining parameters from the tool manufacturers on a micro-level machining. This observation is referring to work by Wuele [12] that has achieved 0.5μm for R_z while Dimov et. al. [14] has managed to produce R_a between 0.13 and 0.44 μm and Vogler [15] with R_a between 0.10 and 0.25μm. These comparable results show that the use of the custom-made MMT does not hinder the micro-milling process to produce a good and satisfactory surface quality. These results are compared with the machining of such miniature features and components that can be achieved on large-scale Precision Machine Tools (PMTs), where this machine is profesionally developed and tested for its performance and precision.

■4.0 CONCLUSIONS

Based on the results from the machining experiments, it has been proved that the MMT is capable in generating micro-components at acceptable accuracies/repeatabilities. Although it was not the scope of this study to seek optimised cutting parameters that result in fine surface roughness, the measured R_a and R_z and also the geometrical values achieved were acceptable giving a respectable range of precision. This provides an indication that the custom-built MMT has been developed to a satisfactory level of precision to enable micro-machining of surfaces with acceptable accuracies.

Acknowledgement

The authors are grateful for the support from the University of Nottingham where the research is carried out. Special thanks go to Universiti Kebangsaan Malaysia and Kementerian Pengajian Tinggi for providing the main author's scholarship.

References

[1] Alting, L., Kimura, F., Hansen, H. N. and Bissacco, G. 2003. Micro Engineering. *Annals of CIRP*. 52(2): 2: 635–658.

[2] Dornfeld, D., Min, S., Takeuchi, Y. 2006. Recent Advances in Mechanical Micro-machining. *Annals of CIRP–Manufacturing Technology*. 55(20): 745–768.

[3] Hansen, H. N., Eriksson, T., Arentoft, M., Paldan, N. 2006. Design Rules for Microfactory Solutions. 5th International Workshop on Microfactories. France.

[4] Bissacco, G., Hansen, H. N., De Chiffre, L. 2006. Size Effects on Surface Generation in Micro Milling of Hardened Tool Steel. *Annals of CIRP-Manufacturing Technology*. 55(1): 593–596.

[5] Lee, K., Dornfeld, D. A. 2004. *A Study of Surface Roughness in Micro-end Milling Process*. Laboratory for Manufacturing Automation. Consortium on Deburring and Edge Finishing. University of California Berkley.

[6] Slocum, A. H. 1992. *Precision Machine Design*. Society of Manufacturing Engineers.

[7] Anonymous. 2009. *Hocut 3380 -High Lubricity Chlorine and Sulphur Free Soluble Oil*. [cited 2009 10/02/2009]; Available from: http://www.goldcrestoil.co.uk/images/stories/13050_Hocut_3280.pdf

[8] *ISO 10791-7: 1998 Test Conditions for Machining Centres-Part7: Accuracy Of A Finished Test Piece*. 1998.

[9] Bissacco, G., Hansen, H. N., De Chiffre, L. 2005. Micromilling of Hardened Tool Steel for Mould Making Applications. *Journal of Material Processing Technology*. 167(2–3): 201–207.

[10] Aramcharoen, A., and Mativengaa, P. T. 2009. Size Effect and Tool Geometry in Micromilling of Tool Steel. Precision Engineering. 33(4): 402–407.

[11] Gietzelt, T., Eichhorn, L., and Schubert, K. 2008. Manufacturing of Microstructures with High Aspect Ratio by Micromachining. *Microsystem Technologies*. 14(9–11): 1525–1529

[12] Weule, H., Hüntrup, V., Tritschler, H. 2001. Micro-cutting of Steel to Meet New Requirements in Miniaturization CIRP Annals-*Manufacturing Technology*. 50(1): 61–64.

[13] Sreeram, S., Kumar, A. S., Rahman, M., Zaman, M. T. 2006. Optimization of Cutting Parameters in Micro End Milling Operations in Dry Cutting Condition Using Genetic Algorithms. *International Journal of Advanced Manufacturing Technology*. 30(11–12): 1030–1039.

[14] Dimov, S., Pham, D. T., Ivano, A., Popov, K. and Fansen, K. 2004. Micromilling Strategies: Optimization Issues. Proceedings of the I MECH E Part B. *Journal of Engineering Manufacture*. 218(7): 731–736.

[15] Vogler, M., Liu,X., DeVor, R. E., Kapoor, S. G. 2002. *Miniaturized Machine Tools for CNC-Based Micro/Meso-Scale Machining of 3D Features. Third International Workshop on Microfactories*.