euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021
www.euspen.eu

Position and force controlled pneumatic chuck for high precision machining

Udo Eckert[1]*, Uri Ben-Hanan[2], Hans-Joachim Koriath[1], Mattias Mende[1], Avi Weiss[2], Rafi Wertheim[1,2], Udi Azaria[3]

[1] *Fraunhofer Institute for Machine Tools and Forming Technology, 09126 Chemnitz, Germany*
[2] *ORT Braude College, Snunit Street 51, PO Box 78, 2161002 Karmiel, Israel*
[3] *Henri Azaria PAL Ltd.*

**udo.eckert@iwu.fraunhofer.de* *Tel. +49 371 5397 1932*

Abstract

This paper presents the development of a clamping system, including force controlled jaws, a method for position and orientation control in the XY, XZ and YZ planes, based on a visual pattern identification and a numerical compensation of the workpiece position, integrated into the machine tool control unit. Reproducible correction of workpiece position and orientation were investigated, evaluated, and combined to form the new adaptive workpiece clamping system to ensure accurate positioning and clamping repeatability. The developed system is made of an air (pneumatic) chuck with 3 clamping jaws, used for holding the workpiece with a defined clamping force, controlled by air pressure. A tilting device combined with a rotating table for inclination adjustment of the XY plane, controlled by the vision identification device, is used to measure and correct the position and orientation of the workpiece. A developed algorithm for X and Y motion of the machine tool axes as a function of the visually identified values enables repositioning of the workpiece after re-clamping. The clamping forces are measured by strain gauges. The design of the associated jaws is based on FEM analysis to ensure small elastic deformations, allowing for accurate clamping forces. The visual identification of the workpiece position and movement algorithm were tested with the pneumatic chuck on a high precision CNC machine tool. The developed system provided in X and Y direction a repeatability of pattern positioning within 1.1 µm, which is three times better compared to the initial chuck reclamping repeatability.

Keywords: machining, precision, clamping forces, pneumatic chuck

1. Introduction

This paper presents a newly developed clamping system using a pneumatic chuck with three force controlled gripping jaws to control workpiece deformation, combined with a visual pattern identification device to ensure high positioning repeatability in re-clamping.

1.1. State of the art

The purpose and features of workpiece clamping devices lies in providing adequate holding, preventing shifting or movement, avoiding workpiece deformation, and also ensuring accurate positioning when re-clamping. The amount of clamping force needed to hold the workpiece is determined by the cutting forces. In addition, the clamping force shall be appropriate to avoid workpiece deformation, thus guaranteeing component accuracy. Clamping chucks, normally used for cylindrical components, operate through mechanical, hydraulic, or pneumatic power. Most of the hydraulic and pneumatic chucks are self-centering devices. Pneumatic chucks are normally used for small, low-strength and flexible components and for micromachining [1]. Workpiece holding devices with sensing technologies and actuation systems are described, for example, in [2]. Hybrid micro-machining devices are implemented in order to achieve better performance [3].

Monitoring and controlling the clamping forces can influence errors of workpiece positioning and production outcome [4,5]. A method to monitor the gripping forces is presented in [6], using the pressure differences of an automatic chuck as a function of friction forces with a wedge mechanism. Other investigations combine force measurements using an integrated sensor in the spindle with workpiece quality and performance; however, the workpiece clamping force is not used as a separate parameter [7].

Force control of three finger adaptive robot gripper, using PID control, is a simple and reliable system to provide an active compliance control through direct force control [8]. Piezoelectric actuators connected to a DOF parallel mechanism enabled motion in the x-y directions and a rotation around the z axis when manipulating a triangular stage [9]. The authors of this paper developed a high-precision clamping system for micro-machining with three independent linear piezoelectric actuators, integrated in three separated force-controlled jaws, ensuring accurate positioning and force controlled clamping. The visual device for pattern recognition is used to identify workpiece position on milling machines. The high-precision clamping system is designed for very low loads, not compatible with standard chucks, and without using the control of CNC machine tool.

The limitations of position repeatability for workpiece re-clamping in manufacturing process chains is caused by workpiece geometrical tolerances, elastic deformation and accuracy of the clamping elements, machining conditions and accuracy of the machine tool [10].

1.2. Challenges, aims and functions

The main challenge of the performed investigation lies in developing a non-rotating clamping system for high quality production of microparts or precision componentes on CNC milling machine tools, ensuring machining, measuring, or accurate additional processing on other machines. The investigation is carried out on a pneumatic and highly accurate clamping chuck, equipped with force-controlled jaws, using a newly developed algorithm for position and orientation control in the XY, XZ and YZ planes. The algorithm implements data from a high precision pattern identification device and numerical compensation of the workpiece position integrated in the machine tool control units. The development is aimed to provide a clamping position actuation of 0.6 µm in X, Y and 2 arcsec angle repeatability of the tilting/inclination in the XY plane with positioning repeatability at target position of < 1 µm. The investigation was carried out on a pneumatic chuck with three jaws and controlled air pressure with a defined clamping force range to ensure workpiece holding. In addition, a newly developed tilting device, combined with a rotating table, enables inclination adjustment of the XY plane, controlled by the vision pattern identification device (see chapter 3.3). The measured position repeatability during testing workpiece re-clamping with the pneumatic chuck without the position and force control system device was 2.7 µm, caused by the contact between jaws and workpiece, which is much lower than the required value of < 1 µm.

The developed algorithm for the X and Y machine tool axes motion uses the visual position identification measurements to control repositioning of the workpiece after re-clamping. An additional challenge comprises controlling the clamping forces within a required range to eliminate elastic deformations, but at the same time allowing for accurate and secure clamping. In numerous cases the workpiece, for example, thin-walled tubes, have to be held with small and accurate clamping forces to avoid deformation. However, the forces should be high enough to avoid, or limit, movement or deflection during machining. Based on prior investigations and cutting data, the newly developed clamping system is designed for a clamping force range of >20 N and up to 300 N, which covers micro up to medium machining conditions.

2. The new clamping system with controlled forces and position using a visual recognition device

2.1 Method, components and functions

Figure 1 shows a block diagram depicting the components and functions of the clamping system with the pneumatic chuck and a pressure control valve. A workpiece with three HV (Vickers hardness) identation marks on the surface for position identation is XY-scanned by a visual device, focussing on the optics in the Z-axis for the best fit of the digital pattern (see chapter 3.3). Providing accurate position repeatability during clamping and re-clamping of workpieces, for example, after being removed and brought back to continue processing.

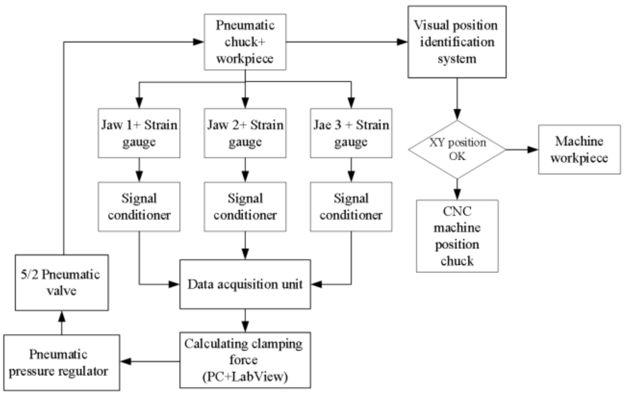

Figure 1. Block diagram of the clamping system with pneumatic chuck, force controlled jaws, a visual position recognition setup and controlled repositioning, using a high precision servo controlled CNC machine

A numerical compensation of X,Y,Z position generates CNC-code for the machine axes and inclination unit so that the workpiece pattern aligns with the optical axis. Each of the three jaws of the pneumatic chuck is equipped with a strain gauge for force measurements. The measured force values are collected and analysed by a data acquisition software checking whether they are within the required range. In case of differences between the measured and pre-defined values, a pressure regulator is activated. A 5/2 electrically operated valve can change the air flow direction for clamping or releasing the workpiece. This two direction valve can be used for external clamping of bars and internal clamping of tubes, or hollow components. The vision pattern identification device can measure the actual workpiece position within <1 µm accuracy. The data is transmitted to a computer and analysed by the developed algorithm and software, resulting in activation of the x, y and z displacement of the CNC machine table and the inclination and angular position of the workpiece. The numerical compensation of X,Y,Z position generates the CNC-code for the machine axes and A,B,C for the inclination unit so that the workpiece pattern aligns with the optical axis.

2.2 Pneumatic chuck and force controlled jaws

The developed system is based on a high precision stationary pneumatic chuck by PML-PAL with three jaws and a self-contained work holding fixture as shown in Figure 2a [11]. The piston acts on the wedge, resulting in the jaws moving on the slanted surfaces in the radial direction (Figure 2b). The maximum stroke of the piston is 3 mm, providing approx. 1 mm movement in the radial direction. The chuck provides automated self-centering of the workpiece with the same clamping forces on all three jaws. The pneumatic cylinder, with pressure control between 0.7 bar up to 4 bar actuates the self-centering clamping function. The maximum pressure for the 64 mm diameter chuck corresponds to approx. 300 N of clamping force on each jaw. The air pressure can be controlled within <0.1 bar, which is reflected in the accuracy of the clamping force. Workpiece loading and unloading is simple, using the air inlet and outlet pressure control supplied through the side of the chuck body. The chuck and the components are produced with very high accuracy providing true position and repeatability of 5 µm and can be mounted on the machine table or on a pallet.

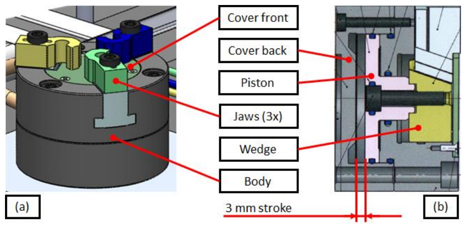

Figure 2. Design and main components of the pneumatic chuck. (a) Chuck with various shaped jaws (b) Chuck cross-section

The jaws comprise force sensors to control the clamping forces during their motion. Strain gauges, piezoelectric and foil type (FlexiForce) sensors were tested for measuring the applied forces. Jaws with various shapes and dimensions were designed using FEA methods and tested to comply with the range of acting forces (Figure 3).

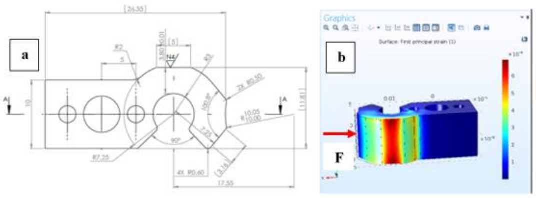

Figure 3. Design of a typical jaw. (a) Dimensions of a jaw for clamping forces 20 N < F < 800 N (b) FEA of strain with 500 µ strain

The maximum calculated and measured strain, for the shown area, amounts to approx. 500 µ strain in the critical section of the jaw (red area). Calibration tests with different jaw shapes and different loads were carried out with the device shown in Figure 4a. Each jaw was calibrated separately. The tested force range corresponds with the defined working range and the calculated FEA values. A typical calibration curve is shown in Figure 4b for acting forces ranging from 20 N to 800 N for the jaw shown in Figure 3.

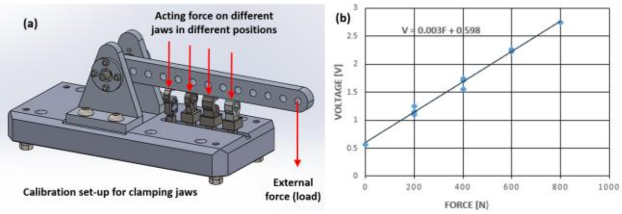

Figure 4. (a) Calibration device for jaws with strain sauge sensors for a force range of 20 N to 800 N (b) A typical force strain calibration curve

2.3 Inclination device

The inclination device (Figure 5) was designed to accommodate an NC-controlled servomotor, including an eccentric with ball bearing. The servomotor rotates the eccentric with an high resolution of 0.0009°/pulse so that the rollers on the eccentric ball bearings slide on the sliding plate, thus generating a movement. Lifting the sliding plate causes an elastic deformation in the selected area. This deformation is realized by the solid-state joint and enables angle adjustment of ± 2°.

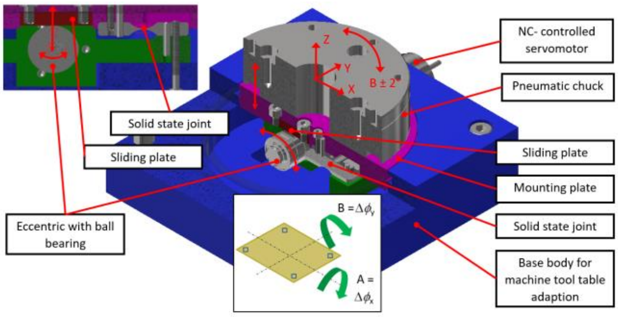

Figure 5. Design and features of the inclination device

The function of the inclination device was investigated on a 3D coordinate measurement machine tool. The measurement showed high repeatability of the rotation as a function of different angle positions. The envisaged angle deviation range of ± 2° was reached with a 3.95° inclination by the system in combination with high stiffness (depending on selected solid state joint) and repeatability of less than 1 µm for the 79 mm mounting plate diameter and masses up to 4 kg.

3. Implementation and testing of the clamping system

3.1 Design and components of the clamping system

Figure 6 shows the main components of the developed and investigated clamping system. The workpiece is clamped in the high precision pneumatic chuck with three jaws (see chapter 2.2), combined with the specially designed inclination device (see chapter 2.3). The new clamping system comprises the workpiece holding chuck with the three force controlled clamping jaws and the visual device for actual workpiece position identification on the CNC machine tool. The measured values were compared to the required positions and used for repositioning the workpiece in the machine space by displacement of the X,Y,Z coordinates and rotations of the A,B,C directions. Displacements were controlled by incremental and accurate movements of the machine tool axes. Moreover, corrections of inclination angles can be performed by the new tilting device and a rotation table capable of adjusting the inclination angle of the X-Y plane within ± 2° degrees in axis A, B with a resolution of 0.002 µm in XY and 0.05 µm in Z and a resulting overall repeatability of 0.1µm.

The device is mounted on a rotating table which is fixed on the CNC machine tool table. The clamping forces of the pneumatic chuck are shown with the inlet and outlet connection to control the pressure and air flow direction. The vision setup for workpiece position identification uses a CCD camera technology [2].

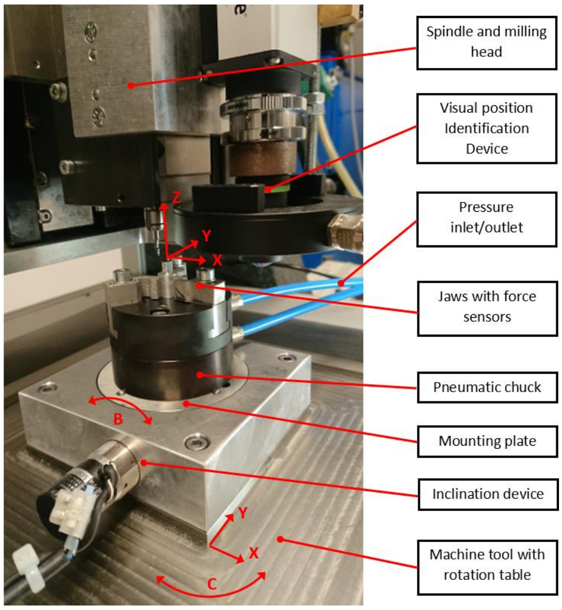

Figure 6. The main components of the investigated clamping system mounted on a highly accurate CNC machine

3.2 Experimental set-up controlling clamping forces

Figure 7 illustrates the assembly of the force measurement setup using a pneumatic chuck with three jaws, each one equipped with three strain gauges. The chuck is connected to the air pressure supply, the pressure regulator and the valve with two directions for clamping and releasing and can be used for external and internal clamping. The strain signals are transformed from the strain gauges via amplifiers to a data acquisition unit (NI USB-6211) for evaluation.

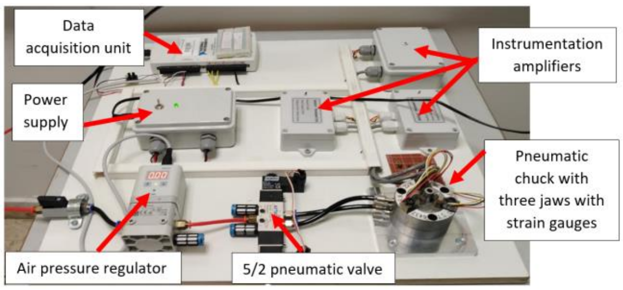

Figure 7. Layout for force measurements and force control of the pneumatic chuck

The results showed that the air pressure is proportional to the clamping forces and can be used as an indicator for force values with a deviation of +/- 5%. The pneumatic chuck was tested with various jaws designed with FEA. The strain gauges, which were designed for 20N<F<300N, were tested with forces of up to 800 N, which corresponds to 500-700 µ strain.

3.3 Vision setup for position identificationn

In order to identify the workpiece position three rhombic HV pattern were pressed on the surface to enable very high accuracy of position and repeatability measurements (Figure 8a and 8b). A typical HV mark is shown in figure 8c. Based on the contour, the CenterPoint of the mark can be calculated. The pattern position of single HV mark in the reference point and the new position after reclamping is shown in figure 8d. The vision device for position identification (camera) is searching for the 3 HV pattern center points of the reference points using the image contrast information in a confocal microscope. The workpiece is released, re-clamped and a measurement of the new position takes place (figure 8d).

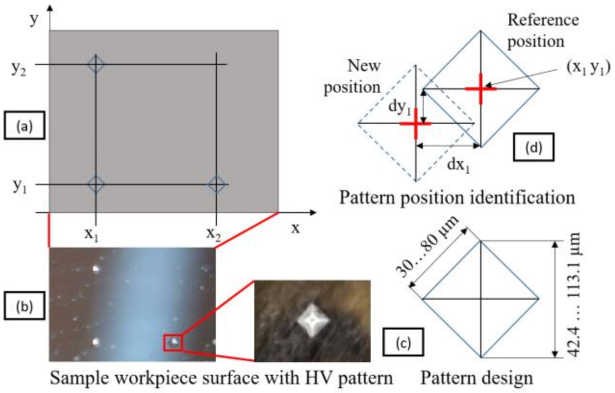

Figure 8. Testing the position identification algorithm using 3 HV patterns with the CCD camera on a CNC machine

The measurements of the first point after re-clamping in relation to the values of the same point, defined as the reference position are used to calculate the required movements (dx1, dy1). The second and third point are identified in the same way for a combined procedure of workpiece repositioning and reorientation.

This two centre points of the pattern and the (dx1, dy1) values (figure 8d) are transferred to the coordinate corrective values in the x and y directions to activate the motion axes drives. Finally, the pattern centre point of the re-clamped position is moving the motion axes of the machine coordinate system. The complex position identification system is characterized by very high repeatability of less than 1µm for pattern identification.

After identifying the marks and implementing the software based on the algorithm the required correction values for exact positioning of the work-piece are calculated and transferred to the control unit, as shown in figure 9.

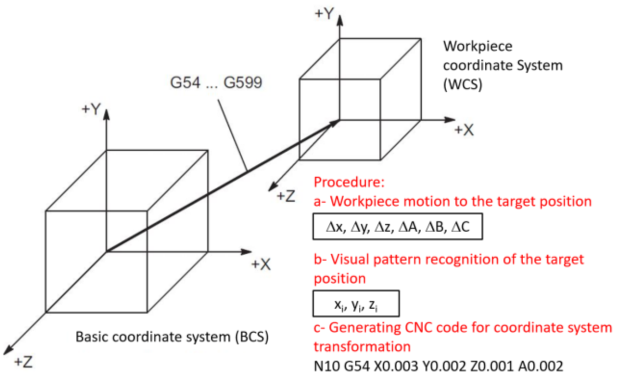

Figure 9. The repositioning procedure using the measured and calculated values to generate the CNC code for coordinate transformation

The basic procedure activated by the new clamping system, carried out on the CNC machine is shown in figure 9. The new position values (X_i, Y_i, Z_i) can be defined in a new workpiece coordinate system (WCS) and the reference position (X_0, Y_0, Z_0) are defined with the basic coordinate system (BCS). The workpiece is moved from the WCS to the BCS, respecting the positioning and rotation (Inclination) movements in order to define the pattern misalignment. The coordinate system transformation is done by the difference vector through CNC code G54. Basic tests in X,Y plane were carried out with the developed clamping systems and the measured repeatability of pattern positioning was 1.1 µm, compared to a re-clamping repeatability of 2.7 µm without the position correction function. The reached value of 1.1 µm is a significant improvement of the repeatability of the pneumatic chuck with 5µm.

4. Conclusions and outlook

The new developed clamping system, tested on a high precise CNC machine tool with repeatability of ± 0.1 µm, provided high accuracy and high repeatability. Comparing state of the art pneumatic and mechanical chucks, the new clamping system controls workpiece position, allignment and clamping function, using a visual device for pattern identification on the workpiece. The developed algorithm for the X and Y machine tool axes motion is using the visual position identification measurements to control repositioning of the workpiece after re-clamping. Position and inclination control of the workpiece in the XY plane is demonstrated in the paper. The investigated pneumatic chuck with FEA designed and force-controlled jaws can be used with clamping forces between 20N and 300N. The developed system provided repeatability of the pattern position of 1.1 µm, compared to the initial chuck reclamping repeatabiltity of 2.7 µm. The next steps will investigate position and repeatability of all axis of the clamping system on a CNC machine tool and the behaviour during milling operation.

Aknowledgement

This research project was performed under the EUREKA program, supported by the Israeli Innovation authority, project number 59410 and AiF GmbH for BMWi Project funding SmartClamp by ZIM Project ZF4016224AT7.

References

[1] Leo Kumar, S., et al., A review on current research aspects in tool-based micromachining processes. Materials and Manufacturing Processes, 2014. 29(11-12): p. 1291-1337.
[2] Wang, S.-M. and J.-J. Lin, On-machine volumetric-error measurement and compensation methods for micro machine tools. International Journal of Precision Engineering and Manufacturing, 2013. 14(6): p. 989-994.
[3]. Gross, S., U. Eckert, and J. Edelmann, New sequential manufacturing process for micro and finishing machining. Procedia CIRP, 2016. 46: p. 559-562.
[4] Denkena, B., D. Dahlmann, and J. Kiesner, Production monitoring based on sensing clamping elements. Procedia Technology, 2016. 26: p. 235-244.
[5] Jantzen, S., et al., Microclamping principles from the perspective of micrometrology–A review. Precision Engineering, 2017. 50: p. 538-550.
[6] Toenshoff, H.K. et al. , Machine Tool Monitoring Appleid to Lathe Chuck, 1990, Annales of the CIRPVol. 39/1/1990, p. 429-432
[7] Brecher, C., et al. Estimation of the virtual workpiece quality by the use of a spindle-integrated process force measurement. CIRP Annales – Manufacturing Technology 68 (2019) 381-384
[8] Sadun, A.S., et al. Force control for a 3-Finger Adaptive Robot Gripper by using PID controller. in 2016 2nd IEEE International Symposium on Robotics and Manufacturing Automation (ROMA). 2016. IEEE.
[9] Acer, M. and A. Şabanoviç, Motion Control of a Redundant Flexure Based Mechanism Using Piezoelectric Actuators. automatika, 2013. 54(1): p. 114-125.
[10] Schubert A., Koriath H.-J., Schneider J., Blank G., 2005, Highest Precision Milling and Process-Adjusted Drive Control. 8th CIRP International Workshop on MMO, p.447-452
[11] Henry Azaria PML-PAL – a brand of high precision air, pneumatic, chucks for machining , certified to ISO 9001