Sub-Micron Referencing System for Ultraprecision Machining Processes

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Abstract

The set-up of ultraprecision machining processes is characterized by manual process steps which require a lot of personal skill and experience to full fill sub-micron requirements in form accuracy. Besides the fact that these manual process steps require a lot of time, they individualize each ultraprecision machined work piece and therefore prevent ultraprecision machining processes from becoming universal and cost efficient machining processes for high precision work pieces. To overcome this deficit, automation solutions are developed within the European Integrated Project (IP) »Production4µ« which enable the realization of efficient ultraprecision process chains with a high level of accuracy. In this paper, a sub-micron referencing system is introduced, which has been developed within this IP to contribute to the high accuracy process chains by enabling the automated and repeatable clamping of work pieces with sub-micrometer deviations from their original position. This does not only enable the efficient combination of different machine-tools and processes but also allows for an increase in product quality.

Keywords: precision machining, work piece clamping, automation

1. Introduction

Clamping and referencing of work pieces in ultraprecision machining is a crucial task concerning the manufacturing quality in terms of form accuracy. Especially, when manufacturing a multiple number of similar work pieces, the clamping accuracy is a major aspect in the production chain. In order to keep the sub-micron accuracy level which is achievable with state of the art ultraprecision machine tools, the only way today is to machine a set of work pieces from the solid as well as an extensive alignment of the diamond tools by test cuts. The more and more complex the designs of optical and mechanical micro components get, the more effort is required for the alignment of the work pieces. By applying novel tool exchange methods which use optical metrology systems the sub-micron form accuracies which are demanded for ultraprecision machined geometries can be fulfilled [1]. Despite the excellent results which are achieved with this method, even a small scale serial production requires a high effort, since the tools have to be exchanged back and forth to machine each individual work piece. The more sophisticated approach is a flow line production as is applied in conventional machining using palletizing and referencing systems which enable a zero-point referencing on each machine tool in the production chain. However, the true repeatability of those systems lies within an accuracy of 2 – 5 µm which is acceptable for conventional machining but exceeds the tolerance limits of ultraprecision machining. Therefore, a passive alignment chuck/pallet system with a sub-micron clamping repeatability has been developed by System 3R within the European Integrated Project (IP) »Production4µ«. The passive alignment is based on the elastic averaging principle. Elastically flexible features in the pallet encounter with highly stiff x, y and z references on the chuck. A high pull force is applied to settle the pallet down on the stiff references and to lock it in a highly stable position on the chuck. An extremely high precision manufacturing of the chuck's reference points ensures for a sub micron repeatability of the pallet position on the chuck. The system accuracy which describes the combination of different chucks with different pallets has been measured with a maximum deviation < 0.5 microns. At Fraunhofer IPT, this sub-micron clamping device has been tested for ultraprecision machining purposes. The results from ultraprecision machining (fly cutting) of a sample work piece are described in the paper. The sample's geometry has been chosen according to a demonstrator work piece which will be realized within the European IP »Production4µ«.

2. MACRO design and working principle

MACRO is a high precision palletized workholding system manufactured by System 3R international AB. In addition to holding the work piece appropriately, the pallet system ensures high repeatable accuracy in location of the work piece. The system also provides for indexing the work piece at 90 degrees with four indexing positions. The system comprises a receiver chuck that is usually fixed on a machine table and a pallet that carries the work piece throughout the process chain. The repeatable accuracy of this system is characterized through maximum deviation of the pallet from its initial position when it is detached and re-clamped on the chuck. For the MACRO a repeatable accuracy of ± 2 µm which is valid for both, with changing of chucks or pallets and indexing of a pallet on the same chuck. This accuracy is achieved through a high precision interface between the pallet and the chuck. Design of the system is based on the principle of elastic averaging which assumes that the system is grossly over constrained but each contact element is relatively flexible and when forces are applied to clamp the system, the elements deform elastically and errors average [2].

The repeatable accuracy of the system over the

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entire usable life is ensured through intuitive design and state of the art manufacturing technology. All contact surfaces on the chuck are rigid while the contact surfaces on the pallet are rigid in Z coordinate and flexible in the X and Y coordinate. The rigid contact surfaces on the chuck are made from carbide steel and all surfaces, both on the chuck and the pallet are grinded with high precision.

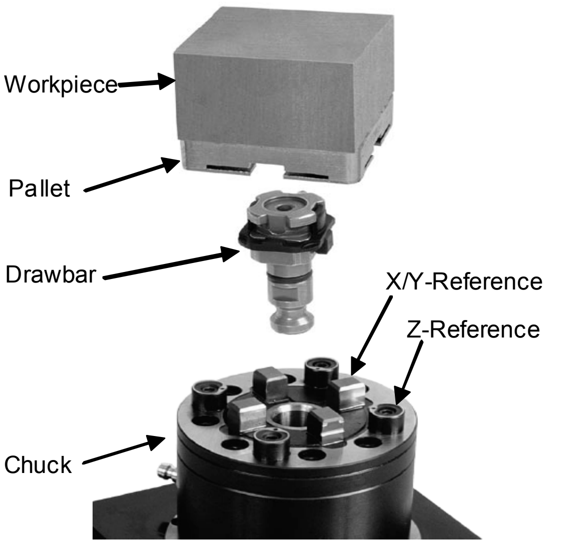

Fig. 1: Elastic Averaging Mechanism in the MACRO System

MACRO-Nano is the next generation system that provides a repeatable accuracy below one micron. This high level of repeatable accuracy in the system is achieved through state of the art manufacturing technology. The rigid contact surfaces both on the chuck and the pallet are prepared through high precision grinding followed by a lapping operation. In this case the design of the pallet has also been improved to avoid sub-micron deflection due to clamping forces. Testing of this system has shown a repeatable clamping accuracy well below one micron. Three chucks have been tested each with ten different pallets for measuring locating precision. The measurements include angular alignment of the pallet along its entire length and breadth, centricity of the pallet and parallelism in Z coordinate. Figure 2 shows the worst of ten precision values for the three chucks in each category of measurement; best observed values are as low as 0.1 µm.

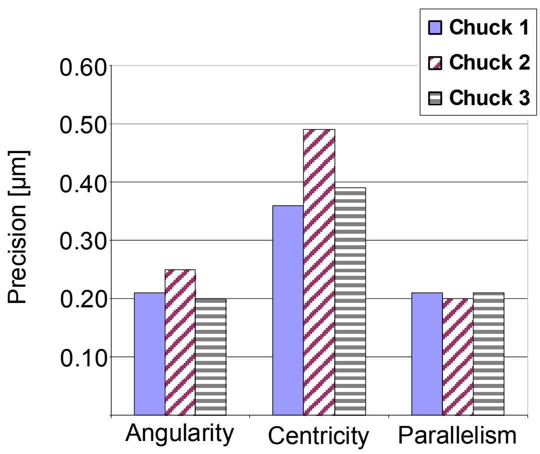

Fig. 2: Precision in pallet location on the Macro-Nano chuck

3. Testing of the macro system in an ultraprecision machining environment

The MACRO-Nano chuck system has been tested for ultrapecision machining purposes at the production site at Fraunhofer IPT. The aim of the machining test was to evaluate the in process behaviour and to measure the deviations of the sample work piece's geometry when using the system as a referencing system.

The machining of the samples as been performed on an ultraprecision machining centre LT Ultra MMC1100-2Z which enables the machining of optical surfaces with a form deviation below 0.1 µm / 100 mm PV. The sample work piece has been machined with a centre feature surrounded by a reference plane as shown in (**Fig. 3**). This sample geometry has been chosen to correspond with mould insert for micro optical components which has been defined as a demonstrator within the European IP »Production4µ«. Another influence on the choice of the sample geometry was the measurability using optical and tactile measurement systems which are described below.

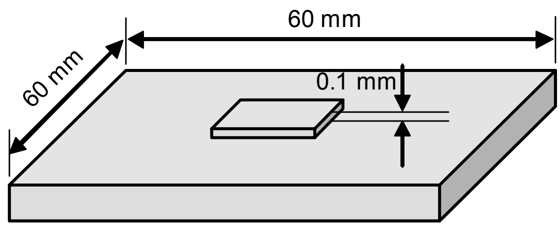

Fig. 3: Test geometry for machining samples

The machining of such a surface geometry requires the subsequent machining of four lower parts towards the edges of the work piece after planing the entire work piece surface. With a conventional ultraprecision machining set up, this is done by indexing the work piece with a highly precise rotary table or by cutting the steps at four different positions within the machine coordinate system. In both cases, the highly precise interaction of at least two machine axes is required. This requirement can be met with state of the at ultraprecision machine tools [3] but still is subject to errors caused by misalignment and inadequate referencing of the work piece in the four different positions. By indexing the work piece about a high precision reference, a symmetric centre artefact can be machined in four identical operations without excessive referencing operations. The previously determined repeatable accuracy of the MACRO-Nano chuck with a maximum deviation < 0.5 µm (**Fig. 2**) is a very promising solution for this task.

3.1 Test Sample Machining

After planing the work piece surface by fly cutting, the machining of the surrounding surface has been started by cutting a ledge at one side of the work piece. The bottom surface of this first ledge has been considered as the reference surface for the latter analysis since it has been machined without detaching the pallet from the chuck and thus represents the accuracy of the ultraprecision machine tool.

The other three ledges have been machined into the work piece surface by indexing the pallet on the MACRO-Nano chuck. In order to do so, the pallet has been released form the chuck, rotated by 90° about its vertical axis and clamped again on the MACRO-Nano chuck. In this way, all four ledges of the surrounding surface have been machined into the work piece without changing the basic set-up the process (Fig. 4).

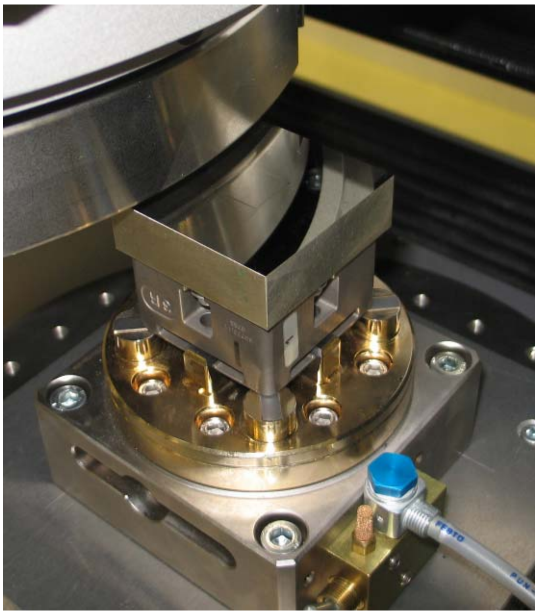

Fig. 4: Sample machining using the MACRO-Nano chuck/pallet system

3.2 Characterization of the work piece geometry

After machining the surface to the specified geometry, the transition seems between the four ledges were clearly visible as straight lines. This is a typical indicator for form deviations caused by misalignments between the different tool paths resp. the four different work piece positions. Taking a closer look at the alignment between the plane of the tool path and the reference plane of the work piece, defined by the MACRO-Nano chuck, it becomes visible, that a relative tilt between the both planes results in a relative tilt between the bottom surfaces of the four ledges. These relative tilts can be considered as an indicator for the accuracy of the MACRO-Nano chuck – if all tilts between the bottom surfaces are the same, the repeatability of the MACRO-Nano chuck is high. Large deviations, indicate a low repeatability of the MACRO-Nano chuck. In order to qualify the orientation of the four bottom surfaces, optical and tactile measurement methods have been applied.

3.2.1 Work piece Characterization by Deflectrometry Measurement

The deflectometry measurement system is a non-contact, absolute and full surface measurement method for reflective surfaces [4]. In general, light hitting a surface is reflected, refracted or absorbed. For the deflectrometry measurement system only the reflected part of the light is important. The more of the surface is mirrored the merrier. Since a surface area is mirroring, if it is microscopic plane. This means that the structures of the surface roughness must be under the measures of the wave length [5]. The primary measurand by the phase measured deflectometry is the local slope of the surface. This occurs by scanning the surface with a laser by detecting and measuring the reflection angles of the beam. Hence the topography is reconstructed and plotted via mathematical integration [6] (**Fig. 5**).

The deflectometric measuring setup consists of:

- A camera
- The surface under test
- A structured illumination, this could be a diffuse reflective screen on which via projector a structure is displayed

The deflectometry impressed with its defined local resolution and furthermore by its possibility for a full surface inspection. The measurement setup is relative rugged against vibrations and other perturbations and may be used for plane and spherical surfaces but also for free formed surfaces [7].

Within the project Production4µ the deflectometry is intended to measure the surface of a work piece which located on a MACRO-Nano pallet which will be placed in the measuring envelope and subsequently be inspected. The measured data will be collected by a data accommodator and provided for the machine control. Afterwards the measuring object will be placed in the process chain again. On the other side it will be investigated to which extent this method can be used for a machine integration. For that purpose the deflectrometry measurement system has been the preferred system to be uses for the characterization of the MACRO-Nano chuck via characterization of the machined surface.

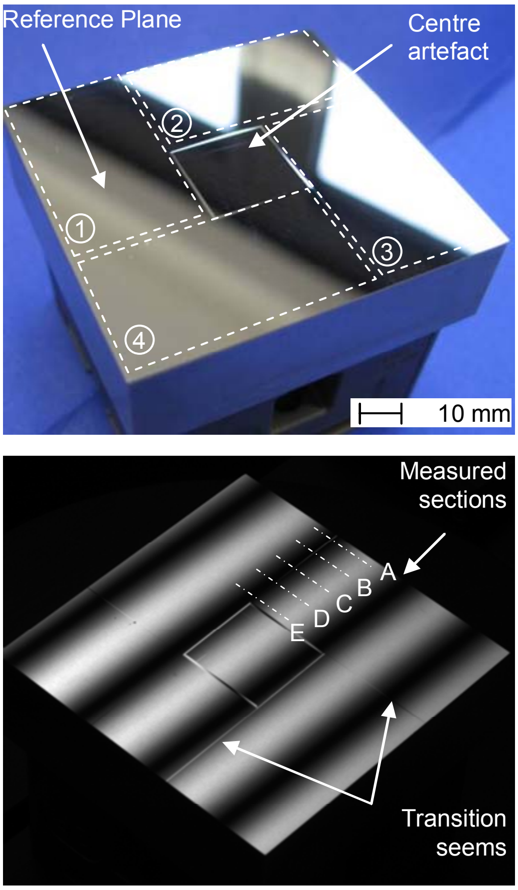

Fig. 5: Test sample geometry and measured features (surfaces: 1-4; sections: A-E)

The information about the deviation between the relative surface orientations was defied by comparing the surface normal vectors . The mean angle between the surface normal vectors was determined to be 0.259° by spatial vector multiplication. The largest deviation from this mean orientation was 0.633° between surface 1 and surface 3 (**Fig. 5**). In terms of repeatability, this means that a maximum deviation of about 0.6 µm has been detected on the work piece surface.

Since special attention must be paid to the right adjustment of the measurement parameter setup which affect the measurement range and the resolution, a alternative characterization of the work piece surface has been performed with a tactile measurement method.

3.2.2. Characterization of the work piece surface by tactile measurement

The characteristics of the transition seems between the four ledges can be considered as an indicator for the repeatable accuracy of the chuck as well – if all seems are equal, the repeatability of the chuck is high. Large deviations between the transition seems indicate a low repeatability of the chuck. Therefore, step heights have been determined by tactile measurement at five sections on each transition seem (Fig. 5). The variations between the step heights (Δh_i) at each section indicate the repeatable accuracy of the MACRO-Nano chuck system. Table 1 lists the average step height at five sections (A - E) at each transition seem. The deviations ($\Delta_1 – \Delta_4$) from the average step height are caused by misalignments when indexing the pallet on the chuck. that the largest deviation from the average step height has been determined to an absolute value of 0.5 µm at the outer section A at the transition seem between ledge 1 and ledge 4. This result confirm the previous measurements. The tactile measurements have been performed using the Taylor Hobson Talysurf system [8].

Section	Average step height	Δ_1	Δ_2	Δ_3	Δ_4
A	2.2	0.1	0.2	0.2	-0.5
B	1.9	0.1	0.0	0.3	-0.5
C	1.6	0.1	0.0	0.3	-0.4
D	1.2	0.1	0.0	0.3	-0.4
E	0.9	0.0	0.1	0.3	-0.4
Centre	0.5	-0.1	0.1	0.4	-0.4

(All values are in µm)

Table 1: Mean step height and average deviations a the four transitions

4. Applications

Within the European IP »Production4µ«, automated process chains for the high volume production of high quality work pieces are realized. Besides the initial precision referencing of work pieces with sub-micron accuracy [9] iterative quality loops are integrated into the process chains. These quality loops are mainly determined by machining, measuring and re-machining of work pieces according to the measured deviations. In order to do so, a highly reproducible clamping of work pieces is necessary. The MACRO-Nano chuck provides trough its passive alignment principle a fast and convenient solution to realize such an iterative quality loop as an cost efficient alternative to active referencing methods.

5. Summary and outlook

With the System 3R MACRO-Nano chuck, a high accuracy work piece clamping device featuring lapped references has been introduced. After the characterization of the repeatable accuracy of the device itself, the MACRO-Nano chuck has been tested in a diamond machining environment. The form deviations of the machined test sample have been characterized by two independent measurement methods with a maximum deviation of < 0.6 µm. No adverse effects on the work piece shape or surface quality due to elastic deformations or vibrations caused by machining forces have been recognized.

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