STUDY ON THE INFLUENCE OF SPINDLE RUNNING ACCURACY AND FEED DRIVE CHARACTERISTICS OF A DIAMOND TURNING MACHINE ON WORK PIECE ACCURACY

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Abstract: *Surface roughness of the order of few nanometers and form accuracies of the order of few hundred nanometers are the requirements of the components produced on a Diamond Turning Machine. Spindle running accuracies and feed drive characteristics of the machine are the significant factors, which are likely to limit the work piece accuracies that can be achieved on the machine.*

The paper presents the studies conducted on the diamond turning machine, developed at CMTI using high precision integrated motor aerostatic spindle and hydrostatic slide driven by high precision friction drive, to establish the influence of the spindle error motions and feed drive errors of the linear axis on the work piece accuracy. The results show the correlation of various spindle errors and feed drive errors of the linear axis with the work piece errors.

Keywords: *Single-Point Diamond Turning, Spindle Error, Feed Drive Error, Diamond Turning*

1. INTRODUCTION

Ultra Precision Diamond Turning often referred as Single-point Diamond Turning (SPDT) involves generation of ultra-fine surfaces of Nano-metric form and surface finish accuracy with mono crystalline diamond tools of cutting edge lapped to atomic level definition. The process is accomplished on vibration free machines of exceptional geometrical and thermo-mechanical accuracies in both spindle rotation and slide movements. Constancy of feed motion at very low federates, realisation of nanometre steps, reversal error & positioning error in manometer range, high stiffness are the requirements from the feed motion of linear axis. Synchronous, asynchronous error & tilt error of few nanometres are the requirement from spindle motion [1].

Prof. Weck has discussed the general framework of error components of a ultra-precision machine tool [2]. Errors can be classified into two categories namely quasi-static errors and dynamic errors. Quasi-static errors are those between the tool and the work piece that are slowly varying with time and related to the structure of the machine tool itself. These include errors such as the geometric/kinematic errors, errors due to dead weight of the machine's components and those due to thermally induced strains in the machine tool structure. The quasi-static errors affects dimensional & form accuracy of work pieces. Dynamic errors on the other hand are caused by sources such as spindle error motion, vibrations of the machine structure; controller errors etc. Dynamic errors play a big role in the surface finish of the work pieces. These are more dependent on the particular operating conditions of the machine [3].

International standards ISO 230-1, Test code of machine tools, provides information on Geometric accuracy of machine operating under no-load or finishing conditions.

ASME B5.57 & ISO 230-7 describes geometrical error components of the axis of rotation and methodology of measurement of spindle errors [4, 5].

International standards ISO 230-2 describes methodology for determination of accuracy & repeatability of positioning of numerically controlled axes of machine tools [6].

Requirements of high precision, slow motion feed characteristics for ultra precision machining has been discussed by Prakash Vinod and R S Suresh [7].

In the present work, the spindle stiffness, spindle running behaviour, spindle thermal drift and the feed drive characteristics of the linear axis have been evaluated by state of art metrological methods including non contact capacitance gauging system and laser interferometer respectively under standard operating conditions. The work pieces have been produced on the machine under the similar standard specified conditions of spindle speed and feed rates. The form & surface finish accuracies of the work pieces have been evaluated and the correlation of the spindle errors and feed drive errors with the work piece errors has been established.

2. SPINDLE, FEED DRIVE, GEOMETRICAL AND THERMO-ELASTIC ERRORS AND ITS RELATIONSHIP WITH WORK PIECE ACCURACY

2.1 Components of Spindle Error Motion

A change in position, relative to the reference co-ordinate axis of the surfaces of a perfect work piece with its centre line concentric with the axis of rotation is given by error motion.

The spindle error motion is described below and depicted in figure 1.

The Spindle error motion can be further segregated into synchronous and asynchronous error [8]

Total error: The complete error motion polar plot as recorded. The total error motion is the total combination of all the error motions of the spindle. It provides a worst-case value giving a preliminary indication of the capability of the machine tool to produce parts.

Synchronous error (Average error): Error motions that are "synchronized" with the rotational speed is known as synchronous error motion. These kinds of motions repeat every revolution of the spindle. A plot of these errors displays lobes that can occur once, twice or at some multiple of times per revolution. This type of motion is also known as out-of roundness motion and it can predict the ability to bore a round hole or to turn a round part.

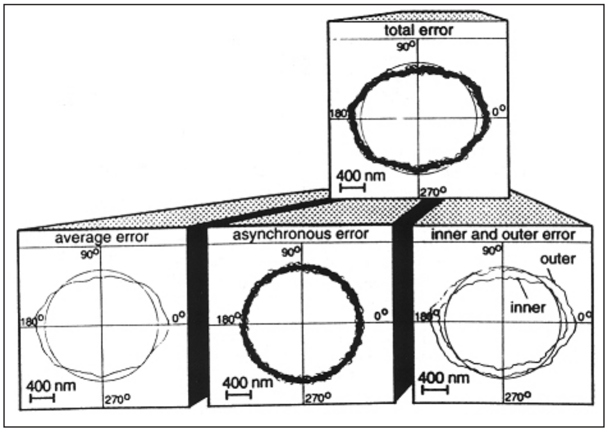

Fig 1. Spindle Error and its Segregation

Asynchronous error: The deviations of the total error motion polar plot from the average error motion polar plot. These motions are not synchronized with spindle rotation. In other words, error motions that are not "synchronized" with the rotational speed of the spindle are known as asynchronous error motions. Bearing "defect" frequencies usually cause asynchronous error motion. They do not repeat on successive spindle rotations. These error motions are depicted by the "fuzziness" of a polar plot, and are related to surface finish. Asynchronous error motions develop due to the interaction of spindle-bearing elements that are rotating at different speeds, like rolling elements, bearing races, rolling element retainers or cages. The errors can also develop from a machine tool's non-structural elements like as in hydraulic pumps or coolant pumps.

The type and characteristic of spindle bearing arrangement has a definite relationship on the total error, asynchronous error and average error of the spindle. On the basis of current technology and knowledge the best results can be achieved using an aerostatic bearing

2.2 Feed Drive Error

The various feed drive tests, corresponding errors and likely effects of these errors are briefed below.

a) Steady state error: This is instability in the slide position under servo hold. The steady state error is likely to affect the surface finish.

b) Error during Constant Velocity test: It is a test method to analyse the uniformity of a feed motion at a constant slide speed. This describes the uniformity of a feed motion at a constant slide speed. For diamond turning, the feed rates are very low but should be very smooth. The feed rates required to get surface finish in manometers can be theoretically estimated using the formula. Unsmooth movements are likely to affect surface finish

Surface finish = $f^2/8r$

Where, f = feed/revolution and

r = nose radius of the tool

c) The step response behaviour: It is a method to determine the smallest step that can be achieved with the feed drive system. This is likely to affect the profile and dimension of work-piece.

2.3 Geometrical errors: The Geometrical errors (straightness, angular and orthogonality errors of motion) of the machine are the main causes for form error of the work piece.

2.5 Thermal drift: The Thermal drift of spindle axis, due to thermo-elastic deformations in sensitive direction w.r.t. tool position, is one of the factors for dimensional and form error of the work piece

2.4 Stiffness of machine: In addition to feed drive, geometrical and thermoelastic errors of machine, the Static and dynamic stiffness of the spindle and slides has a direct effect on the surface finish of the workpieces

3. TEST-SETUP, EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental set-up is an ultra-precision Diamond turning machine, designed and developed for technology development of intelligent machines and research in single point diamond turning (fig.2). The diamond turning machine (fig. 2) has two independent linear axes in "T "configuration. The X-axis carries the tool post and the Z-axis carries the workhead/spindle.

Fig. 3 shows the test-setup for measurement of spindle running accuracy using non-contact capacitive gauging system. The spindle error measurement system consist of; very accurate non-contact dynamic displacement measurement probes or sensors (capacitive type), very accurate sphere target with accuracies down to few tens of nanometers with eccentricity adjustment features, Thermally steady fixture for mounting of the sensors, signal conditioning

Fig 2. The Diamond Turning Machine Used for Experimental Work

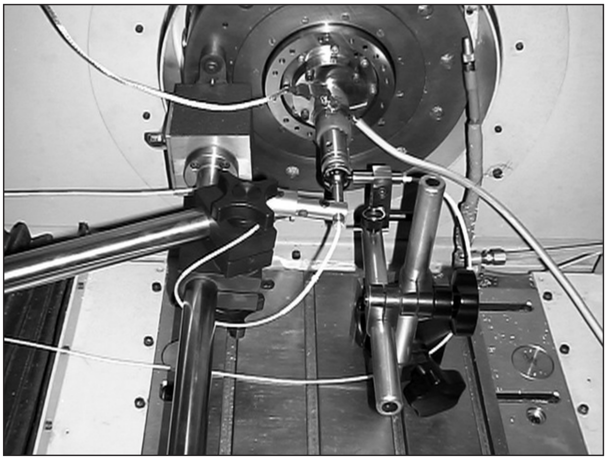

Fig 3. Test Set-up for Spindle Error Evaluation

systems, high speed & high resolution multichannel data acquisition systems, software for data acquisition, analysis and reporting. The system has been used for measurement of spindle running error and thermal drift.

A Renishaw XL-80 Dynamic Laser system (a Helium-Neon laser with a linear resolution of 1 nm) with linear optics has been used for the feed drive tests and geometrical accuracy tests, i.e. for measurement of steady state error, step response, variation during constant velocity test. The straightness and squareness were measured using Non-contact displacement measurement system and metrology artifacts.

Al-6061 flat and cylindrical jobs were machined to establish the co-relation between machine errors and the work piece errors. Mono crystalline Diamond tool (Controlled waviness, 2 mm nose radius), air mist coolant with isopropyl alcohol and vacuum chip extraction system was used for all the machining tests. The machined components were measured using Form Talysurf and Talyrond.

Table 1: Machine error (Spindle Error) Vs Workpiece (flat & cylinder) Errors
Material: Al-alloy-6061, Feedrate: 2mm/min, Depth of Cut = 2 micrometers

Sl. No.	Spindle speed (rpm)	Spindle-Radial error in µm			Spindle-Axial error in µm			Cylindrical jobs (dia 75 µm, length = 30 µm), errors in µm		Flat jobs, dia 80 mm, errors in µm	
		Syn	Asyn	Total	Fund	Asyn	Total	Circularity	Surface finish, Ra	Flatness	Surface finish, Ra
1	276	0.05	0.05	0.09	0.13	0.04	0.17	0.211	0.0132	0.590	0.0117
2	580	0.08	0.08	0.12	0.13	0.04	0.18	0.190	0.0127	0.550	0.0109
3	731	0.07	0.07	0.13	0.13	0.05	0.18	0.178	0.0121	0.508	0.0093
4	923	0.07	0.08	0.12	0.14	0.06	0.20	0.181	0.0117	0.475	0.0087
5	1005	0.09	0.10	0.16	0.14	0.05	0.20	0.210	0.0141	0.500	0.0089

Table 2: Machine error (feed motion) Vs Workpiece errors while machining flats (dia 80 mm)
Material: Al-alloy-6061, Spindle speed =1005 rpm, Depth of cut = 5 micrometres
Steady state error = 20nm

Sl. No.	Set Feed rate in mm/min	% Variation in velocity	Surface finish, Ra, in µm	Flatness, in µm
1	10 mm/min	+/- 4.7	0.0117	0.52
2	5 mm/min	+/- 7.0	0.0070	0.54
3	2 mm/min	+/- 13.5	0.0093	0.48

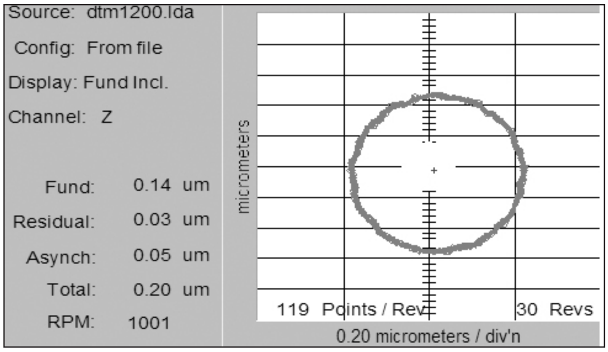

Fig 4. Axial Spindle Error Plot @ 1001 rpm

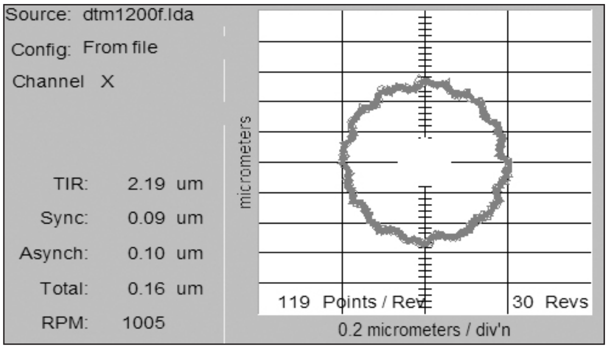

Fig 5. Radial Spindle Error Plot @ 1005 rpm

3.1 Experimental Results and Discussions

The results of various tests are summarised below.

a) Straightness of X & Z slides = 0.5 µm/100mm

b) Squareness between spindle axis & X-axis = 0.8 µm/100mm

c) Parallelism between spindle axis & Z-axis = 0.5 µm/100mm

d) Thermal drift of Spindle axis in X & Z direction w.r.t. tool < 0.1µm (1hour)

e) Stiffness of spindle in radial and axial direction = 150 N/µm

Table-1 & Table-2 shows machine errors and the workpiece accuracies at various standard test conditions. The total radial spindle error and the corresponding asynchronous error increases as rpm increases from 276 to 1005 and the asynchronous error increases as the rpm increases. The surface finish on the cylindrical work piece also increases and follows the asynchronous error. No significant change in axial spindle error, profile and surface finish of the flat work piece is noticed as the rpm increases.

Fig. 4 & 5 shows characteristics and various components of the spindle error @1000 rpm. The radial error plot shows 12 lobes, which is attributed to the number of poles of the spindle motor.

The results tabulated in tanle-2 shows that the surface finish depends upon both the feedrates and variation in the set constant feedrates, used while machining of work pieces.

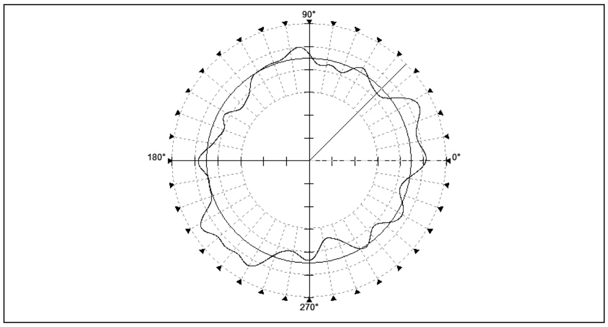

Fig 6. Workpiece Roundness Error @ 1005 rpm Scale: 0.1 micrometers/division, Roundness error = 0.21 mm

Fig. 6 shows the plot of roundness error of work piece @ 1000rpm. About 12 lobes can be seen on the machined work piece, corresponding to the radial spindle error plot (fig. 5)

4. CONCLUSION

Based on the test & experimental results, following conclusions can be made;

Cylindrical work piece: The Spindle radial error-synchronous, straightness error of Z-slide, thermal drift in X-direction and parallelism between Spindle and Z-axis have significant effect on the profile accuracy of the work piece. The Spindle radial error –asynchronous, feed drive errors (non-uniform feed motion, steady state error) & stiffness have significant effect on the surface finish of the components.

The tool will cut a part with the same number of lobes as viewed in the synchronous error motion plot. Manufacturers can measure the synchronous error motions of spindles to find out which spindles they should use for critical jobs.

Flat Workpiece: The Spindle axial error-fundamental, Straightness error of X-slide, Thermal drift in Z-direction & Squareness between Spindle and X-axis have significant effect on the flatness. The Spindle axial error- asynchronous, feed drive errors, non-uniform feed motion, steady state error & stiffness have significant effect on the surface finish.

5. REFERENCES

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