A Proposed Method for Error Prediction and Compensation in Hard Turning

Abstract: *With the advent of new cutting technologies, precision hard turning attracts great interests in automotive, roller bearing and hydraulics industry. Apart from being an environmentally friendly process, it bears enough potential to replace the grinding process. Machine tool design with improved stiffness, damping characteristics, machine-tool system rigidity, and tool-clamping system rigidity facilitates hard turning to achieve better dimensional accuracy up to IT5 on the parts. But several factors affect the machining accuracy and the process reliability and hence the uncertainty about the application of the process. In this paper an analysis of the machine tool requirements to achieve the machining accuracy and the possible error driver factor both load dependent and load independent and possible error sources in a precision hard turning has been schematically represented. The strategy of on-line compensation of the dimensional errors in the process, based on the monitoring of force, acceleration and displacement of machine tool components and prediction of thermal expansion is also proposed*

Index Terms: *Hard Turning, Ground Surface, Machining Accuracy, Error Compensation*

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1. INTRODUCTION

Hard turning process is defined as machining already hardened semi-finished components into finished components from tool steels and high alloy steels with hardness ranging from 50-75 HRC. Size tolerances of +/- 0.010mm can be consistently maintained over a long production run and up to 0.3 µm or better surface finish can also be achieved in hard turning. Hard turning is three times faster compared to grinding and energy per unit metal removal get reduced by a factor of five. The process is environmentally friendly and requires low maintenance cost due to the absence of grinding sludge and coolant, which otherwise is difficult in handling in grinding process. Machine tool required is a CNC lathe, which is more versatile and cheap compared to a CNC grinder. The new cutting materials can be effectively used only on machine tools characterized by high rigidity. From this point of view, the design and materials of the machine tool structure play a key role. As far as the machine structure materials are concerned, the use of materials with high internal damping is necessary in order to strongly reduce the negative effect of vibrations on both tool and work part, and to guarantee the required surface finish. Several materials, such as ferro-cement, hydraulic concrete, polymer impregnated concrete and polymer concrete, have been taken into account as alternative materials to the traditional ones such as welded steel and cast iron.

2. MACHINE TOOL REQUIREMENT

Hard turning as a finishing operation should ensure quality and reliability based on the above parameters discussed. Hence to successfully achieve the fundamental requirement, the process depends on the entire machining system but not just on individual distinct component of the MTW machining system. Advancement in machine tool like improving robustness, increase dynamic stiffness, rigidity of the machine tool in conjunction with the development of the new cutting technologies can commend hard turning to befit economically and a viable process for hard turning. Advance in control capabilities have further improved the accuracy of the machine. Efficient work-holding devices, chip management and cooling system further helped the cause.

Machine tool design involves use of technology like composite filled bases and hydrostatic way systems [1, 2]. Harcrete is a proprietor polymer composite of Hardinge Inc traditionally used in machine base, has damping characteristics up to eight times that of a cast iron. Depending upon the requirement the machine bas can be all composite or a combination of conventional castings with strategically reinforced harcrete cavities. A machine tool equipped with outstanding damping and high rigidity with the polymer concrete bed, irrespective of the insert material and lubrication-cooling technique has a beneficial effect like better surface finish and lower tool flank wear than those by cast iron bed has also been experimentally verified. It was observed that the polymer concrete bed is characterized by vibrations with lower amplitude and resonance peaks than those measured on the cast iron one [3].

Hydrostatic designs or hydrostatic ways are used as internal lands and minute gaps to create pressure by hydrostatic resistance. This fluid film provides a high level of damping in the presence of vibration [2]. The linear ball guides and roller guides of machine tool although exhibit low friction and high stiffness but in a very demanding hard turning application, these contribute a little to damping. Hence such a low level of damping is inadequate to achieve higher level of part quality and tool life. Hardinge has conducted tests comparing the vibration characteristics of machine tool with the hydrostatic guides against the machine equipped with linear ball guides. Results show surface finishes improved 2-fold over the linear ball guides way machine and tool life increased by 38%.[1].

The machine space should entirely be devoid of airborne particulates. Sealing of machine guides ways or hydrostatic ways to prevent entering of granular chips generated in the machine is necessary. The comprehensive machine tool design has to provide the necessary checks. The other critical machine attribute is motion capability and machine accuracy, which depend on a series of component. This includes the combined behaviour of the machine resulting from the axis stiffness, axes resolution, control features, profile accuracy, geometric alignment, lost motions, error compensation. These needs to be seriously considered while designing a machine for hard turning. The other elements, which although not the part of the machine tool but of significance to overall success, they are rigid spindle tooling, rigid tool holders along with a stiffest work holding arrangement. Lack of stiffness of the former two can impair the parts quality due to chattering. While considering spindle tooling, the distance between the spindle bearing and cutting location has to be shorter to minimize deflection, since the deflection will vary with the cube of the exposed length.

3. MACHINING ACCURACY

Precision hard turning demands higher precision machine to eliminate the form and dimensional errors induced by moving components and the machine tools concerning static, dynamic and thermal stiffness as well as accuracy of the spindle system and slides along with the tail stock. Geometric accuracy includes size errors, form errors and positional errors. Surface topography covers the roughness, and the bearing curve of the surface. Major unintended error drive factors, error sources and their relationships are collected from the literature available and are schematically shown in Fig. 1. The unintended errors sources eventually occur are load dependent and load independent. Load dependent error source are cutting heat, (which causes distortion) cutting forces (which creates elastic deformation), tool wear, (which increases the force and heat) and finally insufficient static rigidity and inadequate dynamic stiffness. Error sources independent of loads are uneven allowances, inhomogeneties of the work piece material, manner of surface generation, construction of clamping devices and number of clamping. The effects of all error drive factors are superposed and lead to a relative displacement between cutting edge and surface of the workpiece, thus resulting in error in form, dimension and surface integrity of the final products. The possible error driver factor and error sources in a precision hard turning and the strategy of on-line compensation of the dimensional errors in the process, based on the monitoring of tool wear and prediction of thermal expansion is also studied [4].

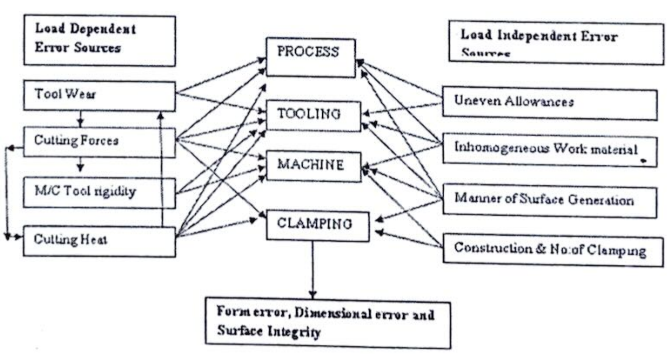

Fig. 1: Major error driver factors and enor sources in precsion hard turning

4. ACCURACY OF HARD TURNED COMPONENT

All components, including cutting edge, tool holder, tool and workpiece clamping, machine spindle and machine tool bed, have an effect on the quality and repeatability of the hard turning process. Current issues in high precision hard cutting are the requirements regarding surface quality and dimensional accuracy of the machined components. Typical surface and dimensional accuracy demands in gear hard turning as shown in the Fig 2 [11]: This typical mass product (9000 parts/week) combines high demands concerning dimensional accuracy, e.g. boring diameter +/- 8 µm, with strict limitations regarding form and surface quality (max. teeth concentricity of 40 µm, bore hole roundness of 7 µm and maximum surface roughness of R_z = 1.6 µm).

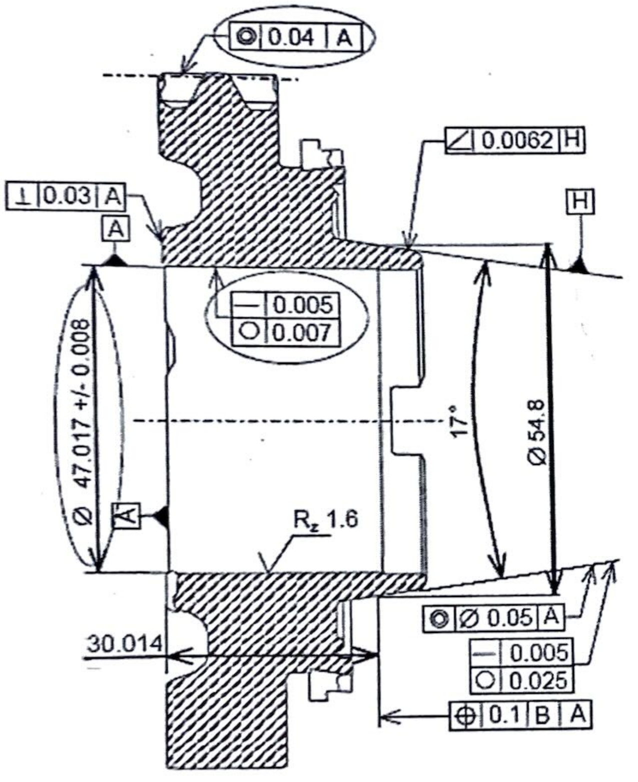

Fig. 2: Typical surface adn dimensional acuracy demands in gear hard turning [11].

Investigation was carried out by inferring the results obtained from an experimental investigation [5] of comparing accuracy of hard turned and ground component on a shop floor environment. This paper referred the machining by both hard turning and grinding of a bored gear as shown in Fig: 3 and as per prescribed accuracy (size, form and positional accuracy). The material of the gears is case-hardened steel: 16MnCr5 (AISI 5115) with hardness 62±2HRC.

In the parts produced in one of the gear as shown in Fig 3 during the investigation of the accuracy, size

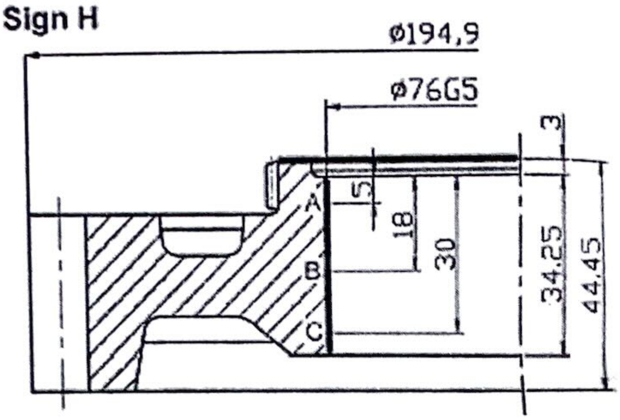

Fig. 3: Gear of Bore Ø 76G5 [5]

deviations were measured as well as out-of-roundness, cylindricity error and parallelism error of the bore's generatrices. The finish hard turning was performed on an advanced machine tool, using a hydraulic 3-jaw chuck and was done in one clamping. Here the gear is clamped with concentrated forces. The finish grinding was done on several grinding machine, with multiple clamping and grinding of the gear were performed with internal traverse grinding.

The measurements of out-of-roundness, cylindricity, axial run-out, parallelism, flatness of the gears produced by both hard turning and grinding are then compared and shown in Fig: 4.

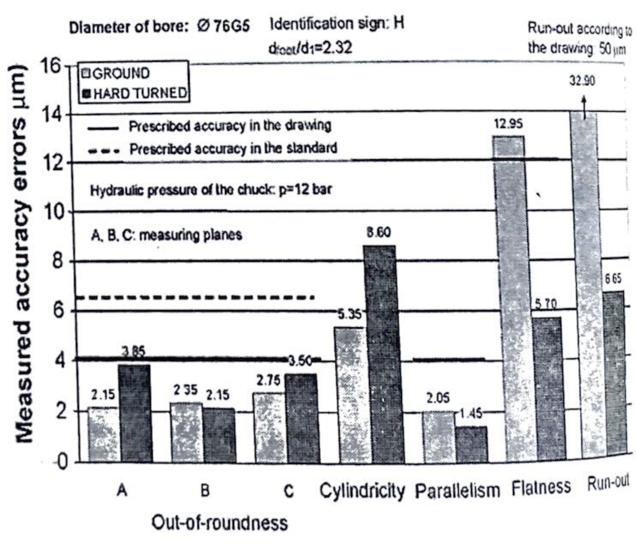

Fig. 4: Summary of the measured results [5]

Although the out-of-roundness is higher in hard turning, it still satisfies the quality prescribed for IT5. The parallelism of the generatrices is also suitable. The cylindricity tolerance is not prescribed therefore, its generation is less important. The flatness is adequate for hard turning, but for grinding it is higher than the permitted limit. The axial run-out is adequate in both hard turning and grinding but much higher in grinding, where it is about five times of the hard turned values. These results show that the ground gear does not fulfill the requirements prescribed in the Table 1 because of its large flatness error.

Table: 1 Prescription of accuracy for Hard Turning [5]

Identification sign and diameter of the bore dt mm	Surface	Permissible Size error	Positional error	Form error	$\frac{d_m}{dt}$	$\frac{L}{dt}$	
H	• bore	+0.023	11	0.004	0	0.004	2.32
0.45 Ø76G5	• face	+0.010		0.05		0.012	

Hard turned gears produced large cylindrical error and out of roundness due to the deforming effect of the 3-jaw chuck, which was also confirmed by another work [9]. As the gears are clamped by single clamping (higher clamping force), and the surface is generated by a single point tool as compared to multiple clamping and linear generative of the grinding wheel, which involves very small force. This problem could probably be avoided if instead of concentrated clamping force, a magnetic or vacuum chuck with distributed force were applied. Ground gears have high parallelism error compared to better parallelism in hard turned gears. Flatness error and axis run out error is prominent (4-5 times higher) of the ground parts compared to the hard turned component [5].

5. ERRORS IN PRECISION HARD TURNING

There are many causes of geometric form errors that can be attributed to the manufacturing process sequence. Form errors are often due to errors in machining and slide way error, but they can also be the result of sagging of the workpiece under its own weight, thermal effects produced during machining, deflections of the workpiece or tool, or stress relief after machining. In broad prospective, the cutting errors imposed on the workpiece can be originated from machine tool, clamping system, cutting heat, cutting process and fixture device.

A. *Tool Wear*

Tool wear governs the geometrical, surface and subsurface qualities of the workpiece. These workpiece characteristics influence important part properties, such as residual stresses. It is known that the tool flank wear in hard turning also has a major influence on the subsurface quality of the workpiece, but crater wear governs the reliability of the operation because crater wear will eventually fracture the tool. Diffusion and chemical reactions are responsible for the crater wear in hard turning. Major wear on the tool flank can also cause the formation of the 'white' layer. Tool wear could have significant effects on dimensional, form and surface roughness errors. The geometry of the tool tip changes as the tool wear as the clearance side will result in loss of the effective depth of cut, which can generate both dimensional and form errors of the workpiece by change of alignment between tool and workpiece.

B. *Clamping*

In hard machining tests the combination of both, a new insert design and an advanced part clamping system, has proved to be beneficial for the process stability Clamping includes the clamping of workpiece

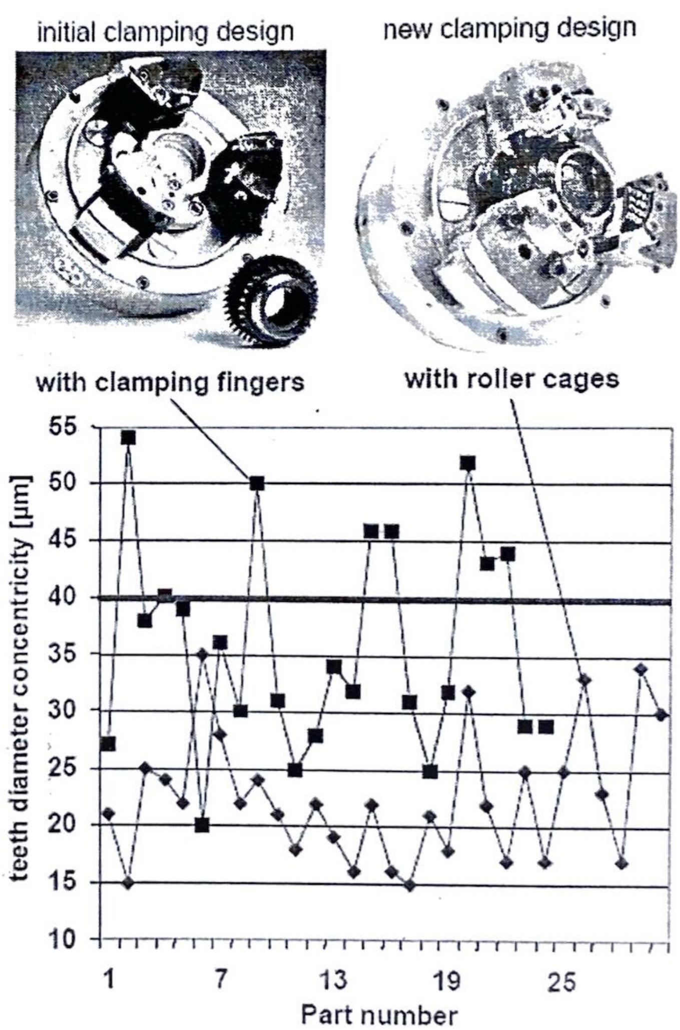

Fig. 5: Part clamping design in gear hard turning [11]

and the insert clamping devices. Deformation may vary with different workpiece and clamping force. Evenly distribution of chucking force is required and hence six jaw chuck is recommended. Magnetic chuck is also suitable but the disadvantage is of chip entanglement during the cutting due to the magnetic force and centre of the workpiece. Possible machining errors may be induced by different type of chucking construction, chucking forces, no: of chucking, chucking rigidity and accuracy. Investigation has also suggested a trend of form errors, which shows higher in chuck side than non-chuck side in precision hard turning of rolling bear due effect of the magnetic force [4]. By changing the part clamping design from a solution with clamping fingers to a roller cage system, the clamping contact length between the chuck segments and the gear part is significantly increased. This ensures a higher dimensional accuracy regarding the teeth diameter concentricity, which is specified to be less than 40 μm after hard turning

The geometric and kinematical errors can also come mostly from inaccuracy of the tool system, such as, insert, tool holder and insert clamping device. Investigation suggested that after re-clamping insert, the repeatability errors at the tip of the insert can reach up to several microns, and the displacement of the tool tip under the cutting load can also reach several microns [8].

Fig. 6 illustrates the way of adapting the tool clamping device which leads, in combination with the modification of the part clamping, to a substantial improvement of the process accuracy Fig.5. The implementation of a flange improves the insert flattening effect and reduces vibrations during cutting. Additionally, the flange improves chip breakage and chip evacuation. As a result, the scatter in tool life is significantly reduced.

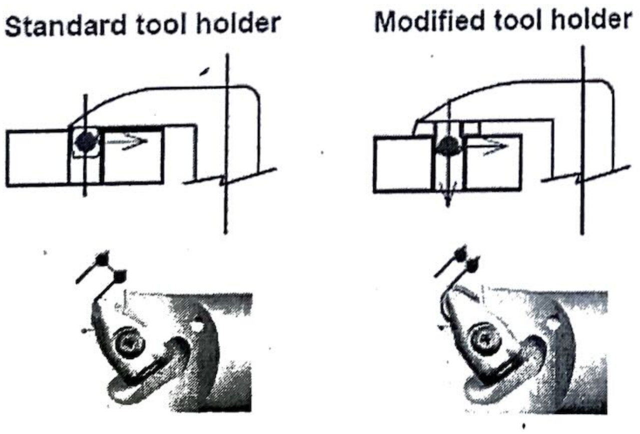

Fig. 6: Tool clamping design.

Higher forces may cause elastic deformation on tool holder and workpiece and change the position of tooling and machine stiffness. In fact, in many cases tool holder reinforced with high density metal or even solid high density metal tool holder, such as carbide tool holder, has been recommended in precision hard turning because of its better thermal conductivity, damping properties and strength..

C. *Vibration*

Machine-tool-work piece machining system [MTWM] in cutting operation is a complex process, the effect of forced and self-induced vibration of MTWM system and its elements result in worsening machining efficiency, precision and less reliable tool operation. Surface integrity, sub surface integrity, surface topography and geometrical accuracy remain the fundamental basic requirement as far as finishing operation is concerned. Tool vibration and tool hangovers are also important parameters as they are deleterious to machining operation. It effects the accuracy of the machined parts, shorten tool life and produce unpleasant noise, hence care should be taken to minimize or suppress vibration by providing sufficient machine rigidity, part piece and set-up rigidity and tooling system rigidity to impart better surface finish.

D. *Cutting Heat*

The thermal effects can contribute more than 50% to overall error of the machined workpiece [7]. Dry condition and high cutting speed is preferred during hard turning. The relative high coefficient of friction and the passive forces cause a significant friction force which transforms into heat. This heat raises the temperature of the work piece material causing thermal expansion, there by deterioting the machining accuracy. Removing coolant from the machining paradigms necessitates incorporation of special design features in machine tools with emphasis on thermo-stress and chip control. The effect of thermal distortion from heat generation of internal and external sources like hot swarf falling which, directly comes in contact with the machine tool element, which have deleterious effect and thus be compensated by increasing the hot rigidity of the machine. Accumulation of dry hot chips, which build up heat in any of the area of machining has to avoided, hence immediate evacuation of hot swarfs has to be done to limit the excessive thermal growth of the machine. Form errors are prominent in dry hard turning this is due to thermal expansion of workpiece and cutting material, which leads to deviation of parallelism on the surface lines. High precision NC resolution of 0.05mm offers the possibility to compensate form errors due to thermal effects. The other way to prevent form errors due to thermal effects is the use of cooling lubricants, which then negates the potential benefits of hard turning in dry condition. The difference in dimensional accuracy between dry and coolant supported cutting process are shown [6]. Dimensional accuracy is not affected by the thermal effect (process heat) and a compensation of the NC control is not necessary during the application of cooling lubricant. Hence, the use of cooling lubricants is recommended if the control resolution is not sufficient to compensate form errors.

E. Machine Tool Structure

Machining accuracy is more often governed by thermal deformation of the machine tool structure than by static stiffness and dynamic rigidity. Since thermal induced error cannot completely be eliminated at the design stage of the machine, the use of control and compensation systems is an inevitable course of action. The machine tool should operate with a low level of ambient vibration over a wide range of frequency hence high dynamic stiffness of machine tool remains a vital machine attribute. Tool life, dimensional accuracy, surface finishes are all dictated by the dynamic stiffness of machine tool. There are practical and economical constraints and limits as to how statistically stiff a machine structure can be effectively designed and produced. Here an adequate level of static stiffness is achieved and then dynamic stiffness is increased by adding damping. Investigation showed finish turning performed on the machine tool equipped with the polymer concrete bed provides tool wear and surface finish values lower than the ones given by the same operations carried out on the turning center equipped with the cast iron bed [10].

6. ERROR COMPENSATION

There are two methods of error calibration, which are pre-calibrated error compensation and active error calibration. In the former case the error is measured either before or after a machining process and based on the measured error the machining process is calibrated during subsequent operations but in the later case the error is monitored on-line and the process is altered there and then [13]. Machining accuracy is affected by the combined effect of the several possible error sources as shown in the Fig 1 but definitely not due to a predominant individual error source. Hence the error compensation system should take into consideration the interaction between the sources rather than consider individual error separately. In order to account for errors on a continuous basis in such a way that the interaction between the various error components could be considered, real time error compensation system need to be employed.

In this proposed method the dynamic parameters of the machine tool components can be estimated with measurements of acceleration, force, displacement or other data from the sensors mounted on the machine tool, workpiece or cutting tool as shown in Fig.7.

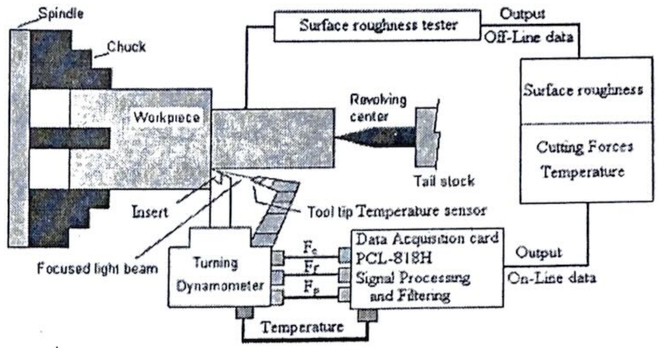

Fig.7: Schematic layout of monitoring set-up

Measurement to be done during free run of the machine to validate the condition of the machine tool and environmental influence on measurements. Measurements to be carried out during machining to validate interaction between the dynamic characteristics of machine tool, tool material and workpiece material. To evaluate signal data and analysis Fast Fourier Transformations technique is necessary to make decision upon the process stability/instability. The input signals from the tests to be recorded with the data acquisition board. Signal data from force-meter and accelerometers can be analyzed with software MATLAB to obtain natural frequencies of machine tool components like chuck, tail stock, slide ways, saddle, headstock etc. FEM can be performed and ANSYS software can be used. Work piece to be modeled as beam element and cutting tool to be represented as combined elements that include spring rigidity and damping. Both supports are to be considered as elastic with high rigidity to include backlash in chuck. Frequency periodograms peaks can be found out and can be correlated with natural frequency of different machine components. Certain value would determine the dominant effect on dynamic behavior during machining. Force can be measured with three main strain gauges on three different locations to find the cutting force, feeding force, thrust force, the signal to be amplified and an A/D convertor to be used. The three components of the forces are to be acquired and analyzed in time and frequency domain. There will be fluctuation of the cutting force, which then influences the cutting power, and thus changes the rate of heat flowing into the workpiece and the tool. On the other hand, the fluctuated, large component of the forces induces significant deflection of the workpiece, which are to be incorporated in the compensation of errors.

As it is relatively easier to monitor the force, acceleration and displacement during the cuttings it is appropriate the error to be compensated by active error compensation method [12]. The thermal expansion on workpiece and cutting tool can be predicted before machining by means of numerical calculations using finite element method, finite difference method and boundary element method. After the error is predicted, it can be compensated for in the CNC tool path. The accuracy of the results by these predictive methods, however, is very much dependent on how accuracy of the input for the numerical calculation and how close the boundary condition are to the practical situation. A knowledge database can be built for the results from numerical calculation for different cutting conditions.

The thermal expansion error under different cutting conditions can be predicted off-line. Based on the comprehensive monitoring system and correspondent thermal expansion of workpiece and tool predicted from FE calculation, error compensation is made through calculation of a compensated contour on the workpiece and generation of new NC code. The NC code is transferred to the CNC system through the communication port between the monitoring system and the CNC's control system.

The thermal effects resulting from tool wear accelerate the shape deviation of the part, which is why compensation strategies become necessary.

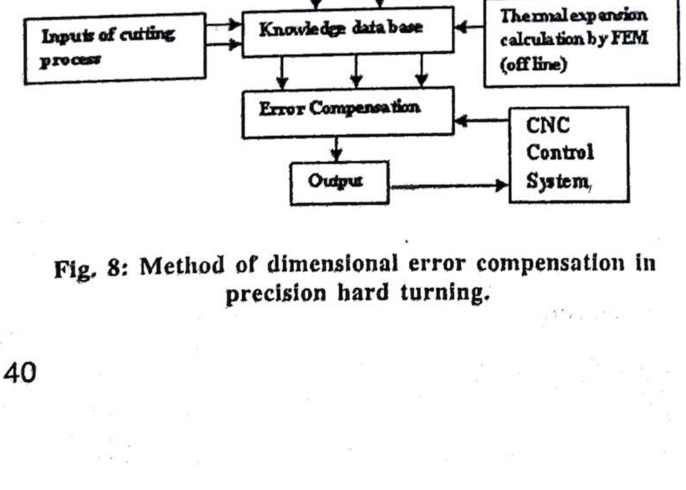

Fig. 8: Method of dimensional error compensation in precision hard turning.

7. Conclusion

Error prediction and compensation is essential issue in super finishing hard turning. Three error-drive factors, including tool wear, cutting forces and thermal expansions, play an important role. These factors directly drive the error sources in process, tooling, machine structure and fixture in the process of error formation on workpiece during hard turning. To predict and compensate the cutting errors, effectively monitoring of tool wear, cutting forces and cutting temperature is necessary. The FE prediction-based error compensation is promising and shows a great potential in improving the quality of hard turned parts. But more sufficient and robust cutting error compensation is to integrate tool wear and cutting force monitoring system with FE model based pre-error compensation.

REFERENCES

(1) Kushnir, R. Newton, "Experimental Evaluation of Machine to Frequency Response Function during Cutting." ASME International Mechanical Engineering Congress and Exposition, Washington, DC 2003, Nov 16-21.

(2) K.L. Wasson, T. M. Sheenan and D. P. Soroka., "Hydrostatic Bearing for Linear Motion Guidance." Patent . 2002

(3) C. Bruni, A. Forcellese, F. Gabrielli, M. Simoncini , "Hard turning of an alloy steel on a machine tool with a polymer concrete bed journal of materials processing technology 2 0 0 8 pp 493–499.

(4) Tonshoff, H.K., and Hetz, F., "Surface Integrity of difficult to machine materials," 2nd IMEC 1986. Session II, pp. 120-136

(5) J. Kundraka, B. Karpuschewskib, K. Gyania, V. Banac, "Accuracy of hard turning." Journal of Materials Processing Technology, 2008, 202, pp 328–338

(6) Liermann. J.,Hartdrehen Walzbelasteter Bauteile. Dr. Ing. Dissertation RWTH, Aachen, 1997

(7) P.A. Mckrowen, M. Weck, R. Bonse, Reduction and compensation of machines, Annal. CIRP 44 (2) (1995) 589-595.

(8) J.M. Zhou, M. Andersson, J.E. Stahl, Development of tool wear and cutting force monitoring system, Int. J. Adv. Manuf. 23 (5–6) (2003).

(9) J. Kundrak, V. Bana, 2003. Geometrical accuracy of machining of hardened bore holes. In: Fourth Workshop on European Scientific and Industrial Collaboration,2003 May 28–30, University of Miskolc Hungary, pp. 473–480.

(10) C. Bruni, A. Forcellese, F. Gabrielli, M. Simoncini, "Hard turning of an alloy steel on a machine tool with a polymer concrete bed"in Journal of materials processing technology 2 0 2 (2 0 0 8) pp 493–499

(11) A.Poulachon, A. Moisan, I. S. Jawahir, " On modelling the influence of thermomechanical behaviour in chip formation during hard turning of 100Cr6 bearing steel", Annals of the CIRP, 2001 50/1: 31-36.

(12) J.M. Zhou, M. Andersson, J.E. Stah, " Identification of cutting errors in precision hard turning process", Journal of Materials Processing Technology 153–154 (2004) 746–750

(13) R. Ramesh, M.A. Mannan, A.N. Poo, Error compensation in machine tools – a review part I: geometric, Int. J. Machine Tool Manuf. 40 (2000) 1235–1256.