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PREFACE

The objective of the Modeling of Machine-tools: Accuracy Dynamics and Control symposium, held at the 1990 ASME Winter Annual Meeting in Dallas, is to create a forum for exchange of information on research and development in metal cutting and metal forming machine-tools and processes. With increasing amounts of compute power and the recent rapid development of sensing and actuation technologies, considerable innovative changes are possible in machine-tool technology. Integration of process and machine control, real-time identification and compensation of machine-tool errors, more powerful and open controller architectures, etc., all of which contribute to the concept of an intelligent machine-tool are now technologically possible. Therefore, attention needs to be directed towards better modeling and analysis of machine-tools and the processes (cutting and forming) performed on them. Thus this symposium.

We would like to thank all the contributing authors for their cooperation and interest in this symposium. Furthermore, we would like to thank the session chairmen for consenting to chair sessions at the symposium and the reviewers for their helpful comments and screening of the papers. We thank the executive committee of the Production Engineering Division for providing us with this opportunity and ASME staff members for their help with this proceedings. Finally, we thank Judi Dimmett for secretarial help and the organization of this volume.

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CONTENTS

MODELING AND ESTIMATION OF MACHINE TOOL ERRORS

Computer Controlled System for Compensating Straightness Error in Grinding
Wang Jie-xin, Xue Bing-yuan, Wang Zhi-jiang, and Pei Ji-yao 1

Improvement of Geometrical Errors by Surface Roughness and Tool Position Controls
M. Shiraishi and H. Sumiya 9

A Screw Coordinate Model of Machine Tool Errors
John C. Ziegert, Daniel G. Olson, and Philip Datseris 23

Accuracy and Dynamics of 3-Dimensional Numerical Control Electrochemical Machining (NC-ECM)
B. Wei and K. P. Rajurkar 33

Evaluation of Machine Tool Design Using Simulation Systems
G. Spur, S. Knupfer, and A. Schüle 47

Model For Computing Quasi-Static and Dynamic Displacements of Turning Centers
G. Spur, U. Schwermer, and A. Schüle 55

Signature of Machine Tool Errors on Surface Texture by DDS
Sudhakar M. Pandit and M. S. Shunmugam 63

A Configuration Independent Approach for Modeling Three Dimensional Error Map for Machine Tools Using Hyperpatch Model and Metrology Plate
H. K. Jan, C. N. Chu, and C. R. Liu 75

MACHINING SYSTEMS DYNAMICS

A Simple Model for Dynamic Orthogonal Metal Cutting
William R. D. Wilson, Carolyn Krug, and Steven R. Schmid 87

The Phase-Shift Between Successive Waves in Dynamic Metal Cutting
Dimitris T. Parthimos and Kornel F. Ehmann 101

Tool Wear and Sound Radiation in Metal Cutting
Habib Trabelsi and Elijah Kannatey-Asibu, Jr. 121

Dynamic Modeling of Acoustic Emission for Control of Peripheral Milling Process
Man Liu and Steven Y. Liang 133

Multi-Input Discrete Time Force Model for Orthogonal Turning
L. Ken Lauderbaugh and Victor Larson 149

INNOVATIVE CONCEPTS IN MACHINE TOOL SYSTEM DESIGN AND ANALYSIS

Development of a Micro-positioning System for Ultra-precision Machines
Yiming Rong, Yaoxiang Zhu, and Qicheng Zhang 161

Thermal Aspects of the Split-Beam Laser Welding Concept
Elijah Kannatey-Asibu, Jr. 175

Curved Surface Machining Through Circular Arc Interpolation
G. W. Vickers and C. Bradley 191

Design and Analysis of a Modular CNC System for Machining Control and Monitoring
Y. Altintas and C. L. Dong 199
Modelling Workpiece Vibrations With Neural Networks
Ibrahim N. Tansel and Alexander Tzirianis 209

FORMING TOOL PERFORMANCE
Estimation of Forming Tool Stress and Life
A. C. Wang, S. J. Pien, M. A. Ripepi, and D. E. Hunter 219
Simulation of Metal Flow and Tool Deflection During Cold Extrusion Process
S. I. Oh, W. T. Wu, J. P. Tang, and A. Vedhanayagam 227
Investigation of an Electric Servomotor Driven Linkage Press for Flexible Forming: Design Synthesis
Timothy J. Nye and Rajiv Shivpuri 237
Investigation of a Servo Motor Driven Multi-Action Press for Application in Sheet Metal Forming
S. Yossifon, D. Messerly, E. Kropp, T. Altan, and Rajiv Shivpuri 255

COMPUTER CONTROLLED SYSTEM FOR COMPENSATING STRAIGHTNESS ERROR IN GRINDING

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SUMMARY

A computer controlled system for compensating straightness errors in grinding was developed. It consisted of following functions: in-situ measurement; data processing and compensatory grinding. The system was successfully used on surface grinder and guideway grinder where higher accuracy workpieces were produced due to compensatory grinding. This paper explains its principle and shows the experimental results.

INTRODUCTION

High straightness accuracy in grinding guideway and flat workpieces is a difficult technical problem. It is affected by many factors such as the error motion of grinder; thermal deformation of workpiece in grinding and so on. Because it is difficult to control these factors causing straightness errors in most of machine manufacturing factories, the grinding accuracy of guideway is usually far below the established ISO standards. To improve the straightness, a machine tool must be constructed with high accuracy requiring advanced technology, which is often difficult and very expensive to achieve. Production costs also increase with increasing machining accuracy requirements. Many efforts were made to improve the straightness accuracy by using error compensatory methods [1],[2]. In this paper, a system for improving the working straightness accuracy of grinder by software compensation is proposed. It has two major functions: measurement and compensatory grinding. A method of using three displacement detectors (tentatively called "the three-point straightness measurement method" and abbreviated to "three-point method") was developed. By means of error separating technique in this method, the motion error of grinder and profile error of workpiece can be obtained simultaneously and accurately by algorithm programmed in microcomputer. In terms of the error values, the accuracy of workpiece can be improved by compensatory grinding. It took short time from measurement to grinding, so the motion error caused by the thermal deformation of grinder and the effects of static loading were also effectively compensated. The system has been tested in lab. as well as workshop with the result of straightness error of workpiece within 1μm/500mm, so that the ISO standards could easily be attained in low accuracy ordinary grinders.

THREE-POINT METHOD

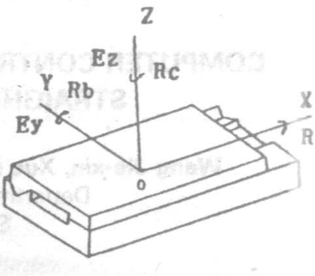


Fig.1 Translational and rotational displacement of the table

The grinder table has as its principal motion a single degree of freedom relative to the guideway. However it will also exhibit parasitic error motions in the direction of each of the other five degrees of freedom if there are inaccuracies in the guideway itself. As Fig.1 shows, the principal direction of motion of the table is along OX, and the error motions are translations along OY and OZ and rotations about OX, OY and OZ, which are defined as Ey, Ez, Ra, Rb, Rc respectively. These errors affect the accuracies of workpiece in varying extents, for example, the straightness of workpiece in vertical plane (XOZ) is affected mainly by Ez, and Rb.

In three-point method, the three probes are installed on the wheelhead, ranked in OX direction at intervals L , as shown in Fig.2, which are used to detect the relative displacement in OZ direction between workpiece and wheelhead, while the table moves along the longitudinal OX direction.

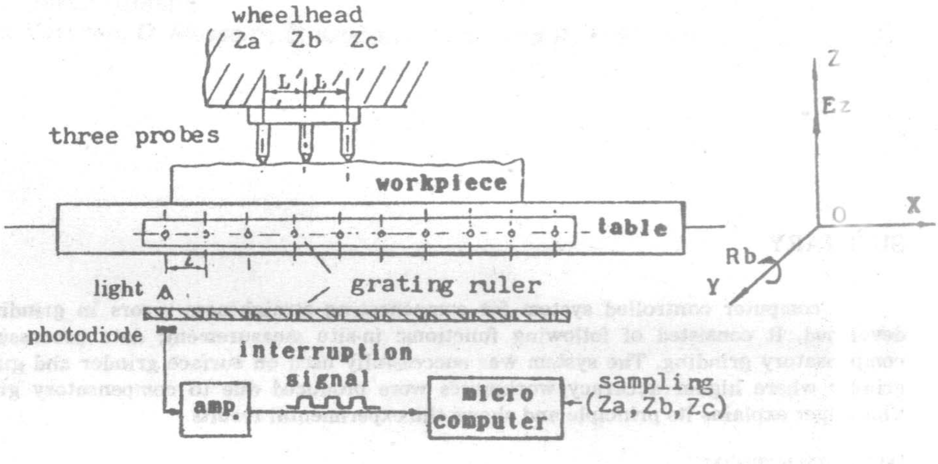


Fig.2 Three-point method

As table moves every L distance, a grating ruler will generate an interruption signal to microcomputer for data sampling of the three probes. When a stroke of table is over, the straightness errors of both the workpiece profile H(i) and the table motion Ez(i), Rb(i) can be obtained by an algorithm in terms of the relative displacement readings of the probes Za(i),Zb(i) and Zc(i), where (i) is sampling sequence number along OX.

$$Za(i)=H(i)+Ez(i)-Rb(i)\times L \quad \text{------ [1]}$$
$$Zb(i)=H(i+1)+Ez(i) \quad \text{------ [2]}$$
$$Zc(i)=H(i+2)+Ez(i)+Rb(i)\times L \quad \text{------ [3]}$$
$$i=1,2,....,N-1$$

Assuming Rb(0)=0, Ez(0)=0 and H(0)=0, the series of H(i), Ez(i) and Rb(i) can be obtained from following matrix equation.

$$\begin{pmatrix} H(i+2) \\ Ez(i) \\ Rb(i)\times L \end{pmatrix} = \begin{pmatrix} 1, -2, & 1 \\ 0, & 1, & 0 \\ -1, & 1, & 0 \end{pmatrix} \begin{pmatrix} Za(i) \\ Zb(i) \\ Zc(i) \end{pmatrix} + \begin{pmatrix} 2, -1, & 0 \\ -1, & 0, & 0 \\ -1, & 1, & 0 \end{pmatrix} \begin{pmatrix} H(i-1) \\ H(i) \\ 1 \end{pmatrix} \quad \text{------ [4]}$$
$$i=1,2,....,N-1$$

If we calculate the straightness error by two end connecting method, the corresponding straightness error $H^*(i)$ is calculated as following.

$$H^*(i)=H(i)-i\times[H(N+1)-H(0)]/(N+1) \qquad \text{------ [5]}$$

$$i=1,2,\ldots,N+1$$

So that the straightness error evaluation H^* of workpiece can be obtained

$$H^*=Hmax.Hmin \qquad \text{------- [6]}$$

where

Hmax --- the maximum value of $H^*(i)$

Hmin --- the minimum value of $H^*(i)$

In order to ensure measurement accuracy, three probes should be calibrated and adjusted carefully on datum plane in advance. To measure the long prismatic workpieces, such as V-guideway of machine tool bed which has two long surfaces, Sa and Sb, we can obtain the straightness errors of both workpiece and table motion in two dimensional space by detecting each surface of them, as shown in Fig.3, then the geomitric errors Hv, Hh of V-guidewy in vertical and horizontal direction are also calculated in vector method, as Fig.4 shown.

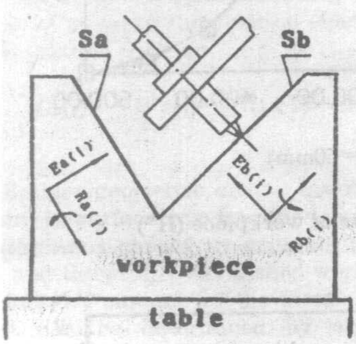
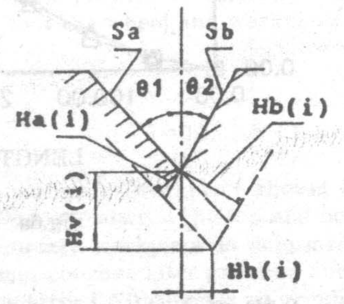


Fig.3 Measurement for V-guideway



-- the desired position of V-guideway

— the real position of V-guideway

Fig.4 The i section of V-guideway

$$\begin{pmatrix} Hh(i) \\ HV(i) \end{pmatrix} = \frac{1}{SIN(\theta1+\theta2)} \begin{pmatrix} COS(\theta2), & COS(\theta1) \\ SIN(\theta2), & -SIN(\theta1) \end{pmatrix} \begin{pmatrix} Hb(i) \\ Ha(i) \end{pmatrix} \qquad \text{-------- [7]}$$

$$i=1,2,\ldots,N$$

where Hb(i) --- profile error of surface Sb in the i section

Ha(i) --- profile error of surface Sa in the i section

if $\theta1=\theta2=45°$, then the formula will be expressed as follow.

$$\begin{pmatrix} Hh(i) \\ Hv(i) \end{pmatrix} = \frac{\sqrt{2}}{2} \begin{pmatrix} 1, & 1 \\ 1, & -1 \end{pmatrix} \begin{pmatrix} Hb(i) \\ Ha(i) \end{pmatrix} \qquad \text{--------- [8]}$$

$$i=1,2,\ldots,N$$

In the same way, we can calculate the table motion errors in vertical and horizontal directions. The flow diagram of measurement system is shown in Fig.5. The output of probes is first amplified, then goes through lowpass filter with a break frequency of 5Hz, so that disturbances coming from environment may be eliminated. After A/D conversion and being processed according to algorithm, the results can be displayed on CRT or printed out in short time. the probes have a sensitivity of 5mv/1μm, and a resolution of 0.1μm, which were maintained the same location at OX direction with the grinding wheel during measurement and can be easily raised during grinding.

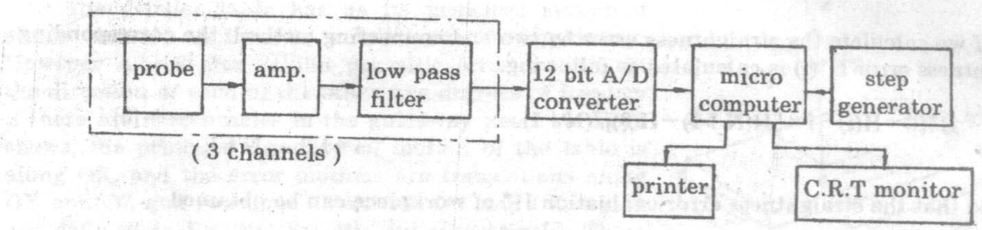


Fig.5 Flow diagram of measurement

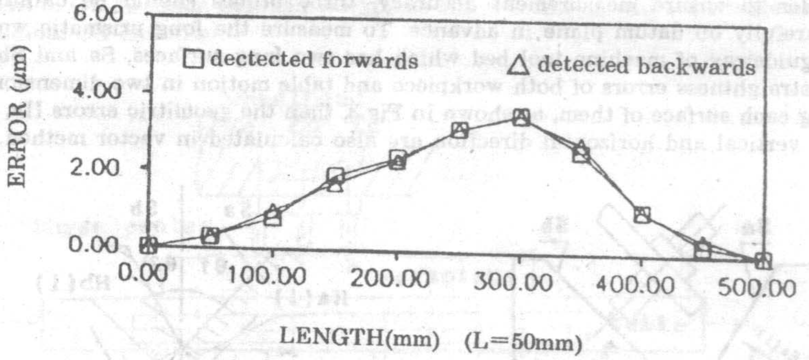


Fig.6a Straightness of workpiece (H*)

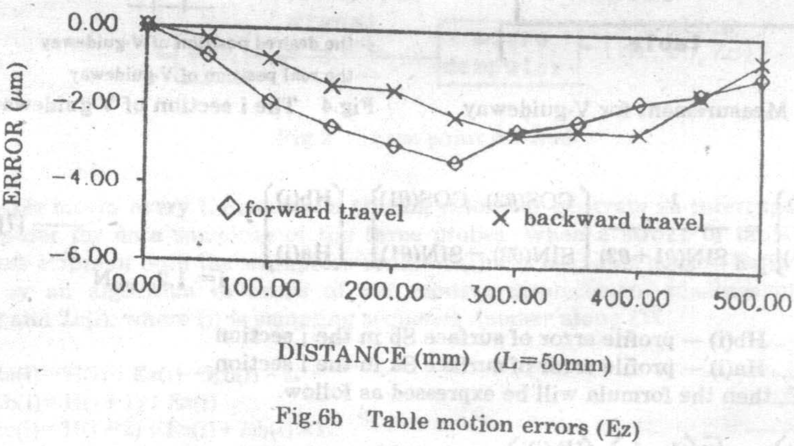


Fig.6b Table motion errors (Ez)

Fig.6 shows the results of measurement for a travel of 500mm on surface grinder. The curves of profile error of workpiece detected in forward and backward travels of table are rather identical, but the curves of two motion errors are quite different due to the change of oil film on guideway.

Fig.7 compares the profile error obtained in the three-point method with that obtained by collimator. It can be seen that there is good agreement between the results.

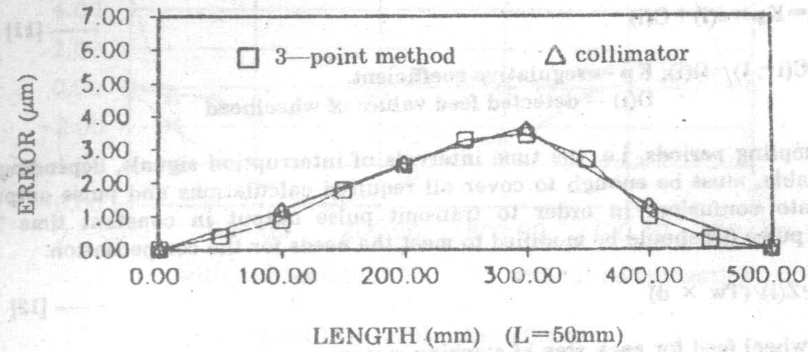


Fig.7 Straightness of workpiece (H*)

COMPENSATORY GRINDING

The motion errors result in a change in position of any point on table and consequently of any point on workpiece mounted on the table. The position of wheel can be modified by an amount equal to the position change Cs(i), so that the wheel and workpiece maintain the desired relative position.

$$Cs(i) = -E^*z(i) = H^*(i+1) - Zb(i) \quad \text{-------- [9]}$$

$$i = 0,1,\ldots,N+1$$

Besides geometric errors, the thermal deformation of workpiece should also be taken account. In surface grinding the temperature difference between the top and bottom surfaces of workpieceis caused by grinding heat. Consequently workpiece is deformed into convex shape and the profile of finished workpiece becomes concave after grinding and cooling. The compensatory amount for the thermal deformation error Ct(i) depends on grinding conditions and it can be determined by experiments or calculation [3]. The total amount of compensation C(i) is as follows:

$$C(i) = Cs(i) + Ct(i) \quad \text{-------- [10]}$$

$$i = 0,1,\ldots,N+1$$

In general, the effectiveness of compensatory grinding depends mainly on positioning accuracy of the wheelhead. Fig.8 shows the simplified diagram of closed loop computer controlled system. When an interruption signal generates from grating ruler, the feed singal of wheel will be detected by a probe touching wheelhead, then be amplified, filtered and A/D transformed into computer. Comparing it with the compensatory command C(i), the computer can modify the amount of compensation output Z(i) in terms of deviations e(i), as follows.

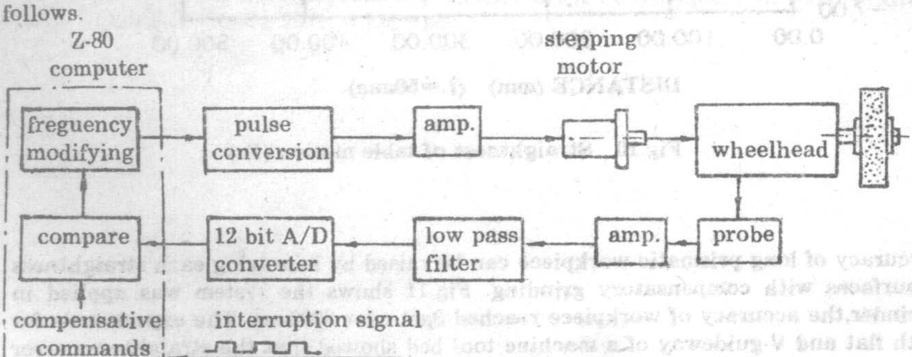


Fig.8 Flow diagram of compensative grinding system

$$Z(i)=Kp \times e(i)+C(i) \qquad \text{------- [11]}$$

where $e(i)=C(i-1)-D(i)$, Kp --- regulative coefficient.
D(i) --- detected feed values of wheelhead

The sampling periods, i.e. the time intervals of interruption signals, depending on the velocity of table, must be enough to cover all required calculations and pulse output, or it could fail into confusion. In order to transmit pulse output in constant time Tw, the frequency of pulse f(i) should be modified to meet the needs for the compensation.

$$f(i)=Z(i)/(Tw \times d) \qquad \text{-------- [12]}$$

d --- wheel feed for each step of stepping motor

Fig.9 shows the straightness curves of workpiece after grinding with and without compensation, The result with compensation is less than 1μm over 500mm length, but that without compensation is more than 4μm over the same length. The motion error of the surface grinder in Fig.10 is more than 2.5μm in 500mm distance. It can be seen that the compensatory grinding system made it posible to produce high accuracy of workpiece in low accuracy grinder.

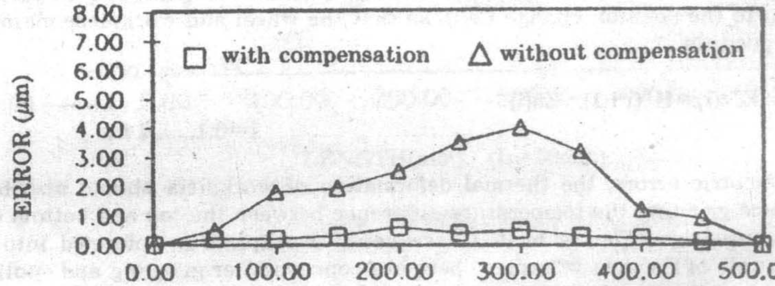


Fig.9 Straightness of workpiece (H*)

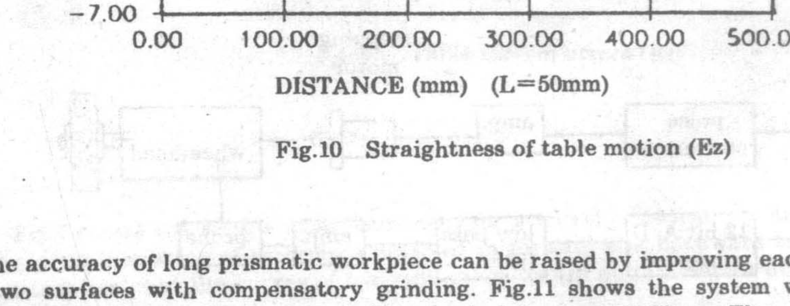


Fig.10 Straightness of table motion (Ez)

The accuracy of long prismatic workpiece can be raised by improving each straightness of its two surfaces with compensatory grinding. Fig.11 shows the system was applied in guideway grinder,the accuracy of workpiece reached 3μm over 3000mm. The experiments for grinding both flat and V-guideway of a machine tool bed showed that the straightness error reduction of more than 50% were obtained with the implemented compensatory system.

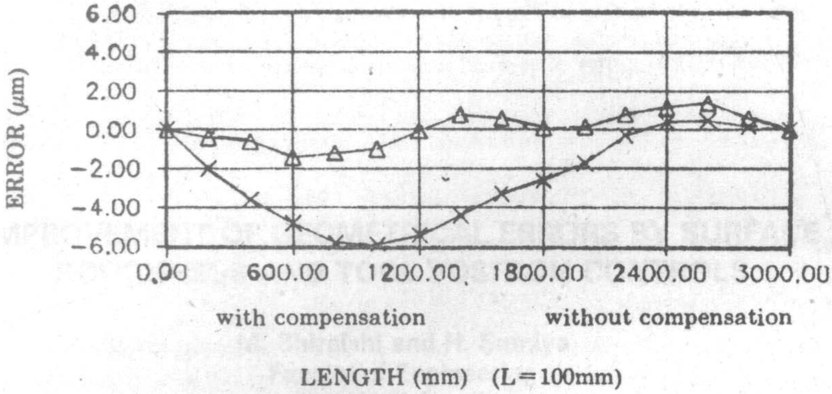


Fig.11 Straightness of workpiece (Hv)

CONCLUSION

(1) The three-point method in straightness measurement has these advantages, the straightness of both the table motion of grinder and the profile of workpiece can be obtained at the same time. Comparing with conventional methods such as collimator, it is easier in adjustment and operation, and can be used in-situ measurement.

(2) The compensatory grinding system makes it posible to produce high accuracy of workpiece in low accuracy grinder, the test results showed the straightness error 1μm/500mm in surface grinder and that of 3μm/3000mm in guideway grinder were rather easily realized. This system could also improve flatness accuracy and implement grinding special surface such as concave and convex.

ACKNOWLEDGMENT

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References

(1) H.Tanaka, "Application of a New Straightness Measurement Method to Large Machine Tool," Annals of the CIRP, 1981/30/1, p.455-459

(2) T.C.Goodhead, "Automatic Detection of and Compensation for Alignment Errors in Machine Tool Slideways," Proc. 17th MTDR Conf. 1976, p.569-576

(3) Y.Takeuchi, "Thermal Deformations and Profile Error of Workpiece in Surface Grinding," Annals of the CIRP, 1976/25/1, p.235-240

IMPROVEMENT OF GEOMETRICAL ERRORS BY SURFACE ROUGHNESS AND TOOL POSITION CONTROLS

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Abstract:

An optimal control in a turning operation has been achieved in order to improve surface irregularities and to reduce dimensional errors. To accomplish this, a simple measuring method of surface roughness has been developed which uses an optical parallel substrate based on a light reflection technique. A tool position control system by the LQI control is designed to reduce the tracking error between tool and workpiece. A cutting tool attached to the specially designed tool servo system is compensated for so that the tracking errors in following a desired tool position are removed. At the same time surface irregularities are smoothed by using a flat bite tool.

1. Introduction

Surface finish is a factor of great importance in the evaluation of workshop production and considerable attention is now being focused on this measurement and control as a means of quality control (McIntosh, 1982., Thwaite, 1984., Clark,1979., Yoo, 1990). If, under cutting conditions, a relative motion takes place between cutter and workpiece, the amplitude of this motion is going to affect the surface roughness of products as well as dimensions. However it is not easy to improve surface finish during machining in comparison with the dimensional improvement.

Since the machining process is so called a "zero-type" control system, tracking errors between the desired and actual tool positions in the steady state will remain for the stepwise depth of cut, thus inevitably generating geometrical errors such as a dimensional error and a roundness error. A number of papers compensating for such errors have been issued on the basis of in-process measurements and most of them are dealing with turning and grinding (Peklenik,1970., Novak, 1982., Mitchell, 1977., Shiraishi,1984., Tomizuka, 1987). However these approaches do not involve the control of surface quality. At present, there is no specified definition which shows a relationship between dimension and surface roughness. Therefore a desired reference value for both roughness and dimension cannot be determined uniquely when these controls are implemented at the same time.

The present contribution is an attempt of the optimal machine tool control to follow a desired tool position as close as possible with better surface finish characteristics. In order to evaluate surface finishes, a new simple measuring method has been developed which uses an optical parallel substrate based on a light reflection technique. It is confirmed from the experimental results that this method can greatly improve measuring sensitivity in comparison with the conventional light reflection technique. According to this measurement, the surface roughness is smoothed by using a larger radius tool, and at the same time a tool carriage control in following a desired cutter position is implemented by the LQI control incorporated with a pneumatic proximity sensor.

2. Concept of the Proposed Control Method

In order to make clear the concept of the proposed technique, the overall procedure of the control method should be described at first according to the flow chart of Fig.1 and the profile model of Fig.2.

(1) Initial cut of 2-3 mm length: Although the surface roughness increases with time resulting from tool wear, the initial roughness is mainly dependent on the tool geometry and the chosen feed rate. Therefore a dimensional error at the very beginning of a cut can be neglected when the depth of cut is not too large. Under this assumption, a turned profile at the part of 2-3 mm length from the start of a cut (part A-B in Fig.2) may be regarded as a reference surface to determine a desired dimension line.

(2) Measurement of initial Rms roughness: After the machining was stopped at the cutting point B, a proposed optical surface roughness measuring sensor measures the Rms (root mean square value of surface height) roughness at the part A-B. This is accomplished to determine the Rms level as a desired dimension line.

(3) Measurement of desired distance between Rms level and the pneumatic sensor head: This distance is set at the part A-B as a desired dimension line. During machining, a pneumatic proximity sensor installed to the above optical system measures the displacement from this desired level.

(4) Initial set of cutting tool position: Both of a regular cutting tool and a compensatory flat bite tool are set at the desired dimension level mentioned above.

(5) Restart of a cut: After these arrangements were accomplished, the machining is restarted from a cutting point B. A tool position control system is designed by the LQI control mode to follow a desired dimension level. At the same time surface irregularities beyond the Rms roughness level are removed by a compensatory flat bite tool.

In summary, a control cut along the desired level implies that the cutting tool compensates for the dimensional error from the prescribed level, and at the same time surface irregularities are smoothed by using a large radius tool.

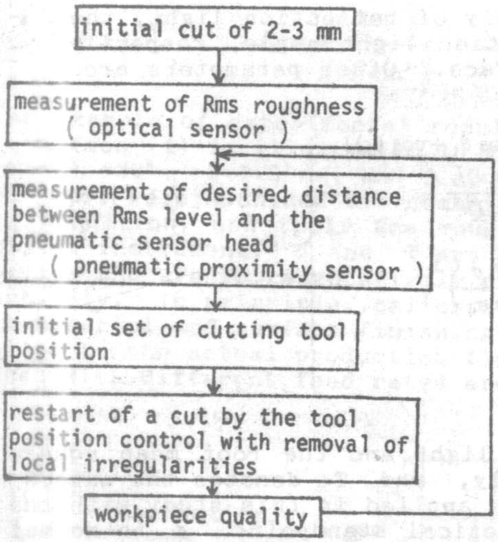

Fig.1 Flow chart of the control method

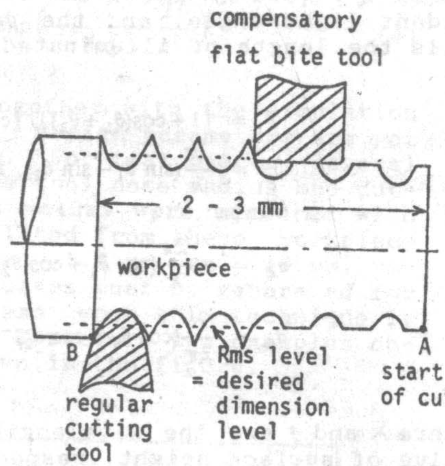

Fig.2 Profile model of a turned surface

3. Measuring Method of Surface Roughness

Figure 3 shows a proposed measuring method based on the detection of normal reflectance of the surface and this can easily measure the Rms roughness value (Beckmann, 1963). A He-Ne laser light having a 2 mm diameter is projected onto a workpiece surface and its normal reflection light passing through the optical parallel substrate is received by the photodetector.

For simplicity of discussion, let us consider a reflectance at the detector D′ in Fig.3, i.e., reflectance before the light passes through the optical parallel substrate. A turned surface is assumed to be a one-directional lay, which is dominantly characterized by feed marks, and Beckmann's theory with respect to the one-directional surface quality can therefore be applied as written :

$$I_0'(\theta_1,\theta_2) = \frac{\sqrt{\pi}F^2 T}{L\,|v_z|\,\sigma}\exp\left(-\frac{v_x^2}{4v_z^2}\cdot\frac{T^2}{\sigma^2}\right) \qquad (1)$$

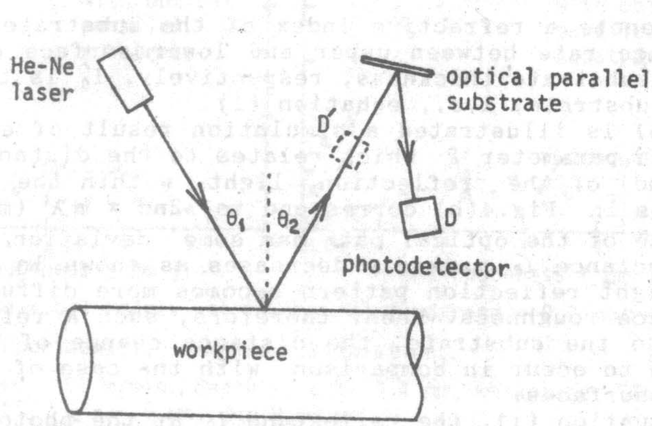

Fig.3 Measuring method of surface roughness