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by G.M. Zhang, T.W. Hwang and G. Harhalakis

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G. M. Zhang, T.W. Hwang, and G. Harhalakis

Mechanical Engineering Department and Systems Research Center
University of Maryland at College Park
College Park, MD 20742 U.S.A.

Abstract

This paper presents a new approach from a systems engineering perspective to integrate tool path control and surface topography generation for the quality control of machined surfaces. This approach is based on a strategic link "variability of material properties - cutting mechanics in microscale - structural dynamics of machine tools - integration of tool vibratory and geometric motions - surface topography generation." By combining experimental and analytical work, this research provides manufacturing industry with a computer-based method to control machined surface topographies.

1. Introduction

Due to the increasing demand for better quality and a great variety of products, manufacturing engineers are faced with a difficult problem of increasing productivity without compromising quality. The surface characteristics of machined parts have been recognized as important factors of the quality control in production. Fine finish surfaces not only provide customer satisfaction for product appearance, but also assure the functionality and reliability of the product.

Controlling surface accuracy during machining essentially involves the control of both the static and dynamic tool path errors. Highly accurate spindle and straight feed mechanisms are being used to reduce the static tool path error. Adaptive control systems that correct the dynamic tool path errors have been used to achieve higher levels of accuracy [1]. Recently, research of the surface topographies formed during machining has attracted great attention to understand the mechanism of surface texture developed, and to identify the surface irregularities generated during machining [2-5]. However, little work has been done to link tool path control and surface topography generation. Factors related to the finish quality of machined surfaces such as tool vibratory motion and variability of material properties, are mainly dealt with qualitatively, posing many difficulties in an effective control of machining accuracy.

This paper presents a new approach from a systems engineering perspective to integrate tool path control and surface topography generation. This approach is based on a strategic link "basic material properties - cutting mechanics in microscale - structural dynamics of machine tools - integration of tool vibratory and geometric motions - surface topography generation." Combining experimental and analytical work, this research provides manufacturing industries with a computer-based environment to control machined surface topographies.

2. Basic Methodology

Our strategy to control the surface topography generation is to study the microstructure of machined surface, to measure the variation in basic material properties relevant to machining, and to relate that information to the tool vibratory motion for quality control of machined surfaces. As a long term goal, we hope that this research will lead to the establishment of the link between standard material properties for machining and the quality of machining processes. This link would represent a significant development in computer integrated manufacturing for monitoring the machining performance and improving the product quality as well.

2.1 Generation of Surface Topography

Figure 1a presents a pictorial illustration of the machined surface generation during a single-point cutting process. From the kinematic viewpoint, the tool cutting point travels along a spiral path in a three-dimensional space during machining. The three directions are related to the three cutting parameters, i.e., feed, depth of cut, and cutting speed. Numerically, the pitch of this spiral trajectory is equal to the selected feed, commonly in terms of the distance per revolution (mm/rev). The surface topography generated by this spiral motion is shown in Figure 1b where the tool nose radius equal to 0.8 mm is used for the purpose of demonstration. When a surface profile is taken along the feed direction, surface characterization indices such as R_a (Roughness average) and PTV (Peak to Valley value), which are commonly used as machining performance indices for quality control of machined surfaces, can be measured on a profilometer.

It is evident that a major assumption has been made to construct the topography shown in Fig. 1b. This assumption is that there is no vibratory motion associated with the cutting tool and the relative position of the tool with respect to the workpiece in the direction of depth of cut remains unchanged during machining. As we have observed, surface topographies generated during machining are significantly different from the one shown in Fig. 1b, but similar to the one shown in Fig. 1c. A comparison of the two topographies shown in Fig. 1b and Fig. 1c reveals that the topography shown in Fig. 1c involves a great amount of surface irregularities caused by the tool vibratory motion during machining.

Study of tool vibration has been extensive and mathematical models to quantitatively manipulate the tool vibratory motion are available [6-8]. In these models, the machining operation system is treated as a closed-loop system having two basic system components, i.e., the cutting process and machine tool structural dynamics. The chip load, a product of depth of cut and feed, serves as the system input. The system response, or the system output, is the tool vibratory motion during machining. A recent study of random tool motion due to the variability of material properties, such as the hardness variation in the material being machined, has provided a useful tool in quantitatively evaluating the effect of hardness variability on the tool vibratory motion during machining [9].

2.2 Control Strategy

The basic methodology in our approach consists of three parts, i.e., development of an analysis hierarchy, creation of a computer-based evaluation environment, and control of the surface topography generation during machining.

To develop an analysis hierarchy, we identify the major concerns of quality control in a factory and arrange these concerns into four different levels shown in Fig. 2a. At the top level, a quality control inspector focuses on the search for a reliable inspection method to effectively detect possible faults in surface quality. At a lower level, or the second level, a production engineer makes a machining plan to assure the surface quality based on the required specifications. The main focus at this level is to control the tool spiral trajectory and to set a limit for the tool vibration during machining. At the third level, a machine tool operator sets the cutting parameters, selects the tool geometry, and carries out the machining operation. At the lowest level of this hierarchy, system parameters related to the control of machining accuracy, such as hardness variation in the material, are identified to form a basis for the analysis hierarchy.

To create a computer-based evaluation environment, we propose a framework to implement the analysis hierarchy on a computer system. Corresponding to the lowest level in the analysis hierarchy, we build a knowledge base to accommodate the information related to the control of machining accuracy. This information includes how basic material properties, such as hardness variability, affect on machining accuracy. Corresponding to the third level, mechanistic models describing the machining operations are used as simulators to manipulate the machining process. Prediction of the tool vibratory motion, both the deterministic and stochastic parts for a given cutting parameter setting, can be made through computer simulation. Corresponding to the second level, a computer program, functioning as an inference mechanism, is developed to use the information related to the predicted tool vibratory and geometrical motions for the determination of an optimal cutting parameter setting.

The work designed to control the surface topography generation during machining corresponds to the top level in the analysis hierarchy. At this top level, a computer-based technique for statistical quality control in automation is developed. The integration of tool path error control and generation of surface topographies not only enables the quality inspector to effectively discover existing faults associated with machined surfaces, but also allows him/her to identify the possible causes of error and send this quality information to the other levels of the analysis hierarchy to request corrections in the machining process. Such an integration forms a closed-loop control of machining accuracy in a computer-integrated manufacturing environment.

3. Implementation of Surface Topography Control

3.1 Mathematical Modeling

Common sense dictates that using quantitative mathematical models to represent the machining operation system as well as the basic material properties relevant to machining is an essential step in implementation of this strategy for surface topography control. In our work, the following three mathematical models shown in Fig. 3 are employed to establish the link between the material properties and machining accuracy.

1. A machining system model to describe a machining process such as turning.
2. A statistical model to represent the basic material properties such as the nonhomogeneous distribution of hardness in the material being machined.
3. A topographical model to represent the surface texture formed during machining.

As illustrated in Fig. 3, the framework represents a mapping to transform the raw material into a quality product in terms of surface finish. In this mapping, the statistical model serves as the stochastic part of the input to the machining system model. The machining system model manipulates the tool vibratory motion. Numerical data of the tool vibratory and geometrical motions are fed into the topographical model for construction of the machined surface.

3.2 Software Development

The translation of the three mathematical models into an integrated computer evaluation program, which could be used effectively for the control of machining surface in the factory, is based on modularity theory and the concept of shared data bases.

The developed software consists of the five modules shown in Fig. 4. These modules are for the user input, the basic material property, the machining process, the tool geometrical motion, and the topography generation. As an example to demonstrate the software development, consider the material property module. The experimental data obtained from measuring the hardness of the microstructures and identifying the microstructural distribution in the material being machined are stored in an electronic file. This file is used as the input to the basic material property module. Applying the random excitation modeling technique proposed in [10] to analyze this data, a normal distribution model to represent the nonhomogenous hardness distribution in the material being machined can be formulated with mean and variance as its two parameters. These two parameters, carrying the synthesized information of the experimental data, serve as input to the machining process module and will also be used to characterize the dynamic variation of the cutting force in the tool vibration evaluation.

The basic structure of the shared database used in our work is depicted in Fig. 4. Each record of this database consists of two classes of data: (1) module exchange data, and (2) operational data which is commonly used among the 5 modules. As illustrated in Fig. 4, the module exchange data describes the source and destination of the flow of information among the five modules. The operational data residing in the fields called common blocks are those system parameters which appear in more than one module during the program execution. For example, parameters related to the tool geometry will be used in both the vibration evaluation module and the topographical generation module. Therefore, data related to the tool geometry is structured in the shared database. This shared database is accessible, extensible, and consistent to all the modules. As illustrated in Fig. 4, the information stored in this shared database is constantly transferred into the knowledge base for future reference, thus updating the information stored in the knowledge base.

3.3 Experimental Work

The experimental work involved consists of two parts. The first part is the calibration of system parameters for a given machining operation system. As indicated previously, the independence of the individual modules built in this computer-based evaluation environment offers the flexibility to deal with different machining operation systems. This evaluation environment can be used for turning, boring, drilling, and milling. However, numerical values of the system parameters relevant to the structural dynamics of machine tool, such as structural stiffness, damping coefficient, and equivalent mass, have to be determined on a case by case basis through experimentation. On the other hand, different materials possess their own distinct material properties such as hardness, ductility, and conductivity. Even for an identical part material, difference in the microstructural distribution will have a significant impact on the surface topography generation during machining. The two figures presented in Fig. 5 are the experimental results for identification of the microstructural distribution in a mild carbon steel. Figure 5a is the sample image taken from a specimen and Fig. 5b is the sample image after the contrast enhancement. Black areas represent locations of pearlite structures and white areas represent locations of ferrite structures. The digitized data is stored in an electronic file to be fed to the material property module.

4. Industrial Applications

Today's innovations in manufacturing technology are driven by demands to maintain a consistently high level of product quality. There is a pressing need to implement a quality control system that assures a high level of product quality, without relying totally upon the traditional product inspection process to provide quality assurance. Our research work offers manufacturing industries a unique approach to achieve this goal of consistency. Three industrial applications are illustrated in this section.

4.1 Topographical Visualization and Roughness Average Evaluation.

In this industrial application, we demonstrate how basic material properties, such as hardness variability in the material being machined, are linked to their effects on the finish quality of a machined surface. The strategic linkage embodied in our approach is "basic material properties - cutting mechanics in microscale - structural dynamics of machine tool - integration of tool vibratory and geometric motions - surface topography generation - quality index evaluation."

Examining Fig. 5b, the hardness variability results in the nonhomogeneous distribution of the microstructures in the material. During machining, as the cutting tool passes over the workpiece, the cutting edge will encounter hard spots if the edge is in contact with the pearlite structure and soft spots if in contact with the ferrite structure in the present example. In our approach, we are able to quantitatively evaluate such dynamic variation of the produced cutting force. The mechanistic model representing the dynamics of the machine tool maps the cutting force variation to the tool vibratory motion. Integration of the tool vibration with the tool spiral trajectory, or the tool geometric motion, enables us to determine the instantaneous tool location during machining. Taking the geometry of the cutting edge into consideration, our approach provides a vivid picture of the surface topography generation during machining. The two surface topographies shown in Fig. 6 represent machining SAE 1015 low carbon steel on a Placemaker experimental lathe at two different feeds. Examining the surface texture displayed in the two topographies, such visualization offers great help to the operator for monitoring the machining process. For example, excessive roughness usually indicates that the tool has become worn, whereas excessive waviness usually indicates that excessive vibration has occurred during machining.

The key advantage to our approach is that it offers a computer vision of the evaluation of surface characterization indices, such as roughness average R_a, due to the availability of the numerical database prepared for the topography generation. Instead of taking actual measurements from the machined surface, surface profiles at specified locations on a machined surface can be constructed. Figure 6b presents two roughness profiles taken from the two surface topographies shown in Fig. 6a, respectively. As a result, each of the two associated R_a values can be directly obtained through the following calculation.

$$R_a = \frac{|y_1 - y_{average}| + |y_2 - y_{average}| + \dots + |y_n - y_{average}|}{n}$$

where $y_1, y_2, y_3, \dots y_n$ represent the heights of individual points on the roughness profile. The average value, $y_{average}$, is the average of these height values, and n is the number of points taken on the roughness profile. Hence, this research provides production engineers with a consultation tool for cutting parameter settings. For given part materials, cutting tools, and machine tools, the developed computer-based environment can support the decision-making process of selecting the cutting parameters such as feed, depth of cut, and cutting speed, by comparing the simulated machining performance with the blue print specifications. Such a capability meets the increasing demand in machining operation planning, particularly in NC machining where the selection of the cutting data has to be made during the programming stage.

4.2 Quality Inspection for Roughness Average Measurements.

As we have noticed, the R_a evaluation, based on the profiles constructed from the simulated surface topography, is location dependent. In general, R_a values evaluated from the profiles taken at different locations will not be equal. This suggests that the R_a index should be dealt with statistically in the quality inspection program. We expect that results either from the R_a measurements taken on a machined surface or from the R_a evaluations based on the simulated surface profiles obey a normal distribution with mean and variance values given by

$$R_{a\ mean} = \frac{1}{h} [R_{a1} + R_{a2} + ... + R_{ah}]$$

$$\sigma_{Ra}^2 = \frac{1}{h} \Sigma [R_{ai} - R_{a\ mean}]^2$$

where h represents the number of roughness profiles taken during the evaluation.

Table 1 lists twelve R_a values calculated from each of the two surface topographies shown in Fig. 6. The means and standard deviations are also calculated from the listed data. The $R_{a\ mean}$ for a feed of 0.30 mm/rev, equal to 4.24 μm, is significantly larger than the $R_{a\ mean}$ for a feed of 0.10 mm/rev, which is equal to 3.38 μm. Such a difference is mainly due to the large pitch of the spiral trajectory associated with feed = 0.30 mm/rev. The two standard deviations (1.82 μm for feed = 0.10 mm/rev and 0.70 μm for feed = 0.30 mm/rev) also differ from each other significantly. The large standard deviation, σ_{Ra} = 1.82 μm, is associated with the small feed set at 0.10 mm/rev, indicating that quality inspection using the R_a measurement requires a sufficient amount of profiles to assure a satisfied prediction. In reality, this implies that a large number of traces should be taken during the quality inspection of machined surfaces fabricated with small feeds because of the presence of a large value of σ_{Ra}. On the other hand, it is evident that a small value of σ_{Ra} indicates a few number of traces would suffice the inspection accuracy. Therefore, this research provides an insight for the quality inspection of surface finish. Because of the variability in the R_a measurement, the number of traces, which should be taken to assure the inspection quality, is related to the numerical value of σ_{Ra}.

4.3 Control Parameters in the Surface Topography Generation.

Productivity and quality improvement requires an active control of the finish quality of machined surfaces. Methods to achieve fine finish surfaces are numerous. Using a small feed to reduce the pitch value of the tool spiral trajectory is a good way to achieve a smooth surface. However, it suffers from a low productivity because of the low material removal rate associated with small feeds. Using a machine tool with high rigidity is also a good way to improve the finish quality because it reduces the magnitude of tool vibration effectively, leading to few surface irregularities formed during machining. However, we have to pay a high cost for equipment investment, which is hardly justified for batch production.

In this paper, we present a new approach to improve the surface finish through the control of microstructures in the material being machined. We recognize the important role that the geometric shape and size of microstructures can play to homogenize the effect due to an uneven distribution of microstructures in the material on the cutting force variation during machining. Figure 7a represents the microstructures in SAE 1015 material after a spherized heat treatment. Figure 7b is the surface topography under the machining conditions compatible with those used for generating the surface topography shown in Fig. 6. After comparing the two topographies, a significant difference between them is less roughness observed from the topography shown in Fig. 7b. This indicates that the tool vibration is somehow attenuated when the material through the spherized heat treatment is being machined. It is evident that sphericity of microstructures reduces the chances for the cutting edge to meet extremely hard spots and extremely soft spots, keeping the random tool motion during machining at a minimum level. A quantitative description to control the surface irregularity generation through microstructural analysis and its industrial applications can be found in [11].

5. Conclusions

A computer-based environment for the control of surface topographies formed during machining has been developed. By integrating the analytical and computational techniques of control engineering and machining science with software advances, this research presents a general picture of productivity and quality improvement in the manufacturing domain from a systems engineering perspective. From the results and discussions, the following conclusions can be drawn.

1. Basic material properties, cutting dynamics, machine tool structural dynamics and tool kinematics are identified as the four essential parts to control the surface topography generation. As a demonstrative example, the effect of the microhardness variation in the material being machined on the surface irregularity formation has been studied. It indicates that control of microstructural characteristics is an effective method to improve surface finish quality. Because of the associated low cost, this method best fits batch production for manufacturing industries.
2. A unique contribution presented in this paper is the development of computer vision of surface roughness characterization for quality control. The three-dimensional topographies visualize the surface texture formation. Such qualitative information would be vital for either an on-line sensing system or the operator to monitor the machining process. The presence of the numerical database of topography information offers construction of a surface profile in any arbitrary locations. Such quantitative information forms a basis to formulate effective quality control programs which take into account the effect due to the variability among the inspection measurements on the quality assurance.

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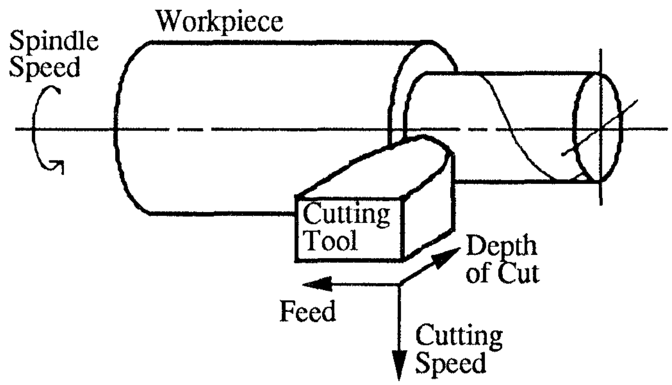


Figure 1a Single-point Cutting Process

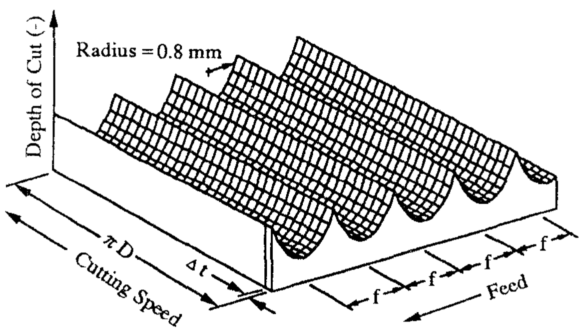


Figure 1b. No Tool Vibratory Motion

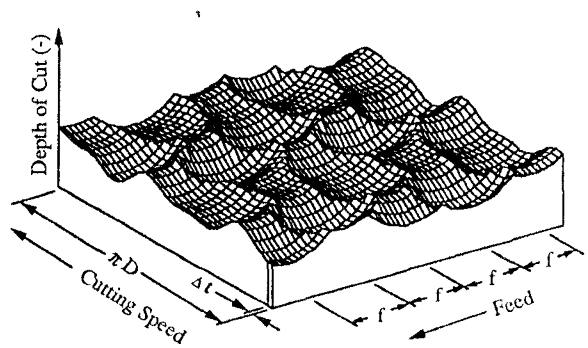
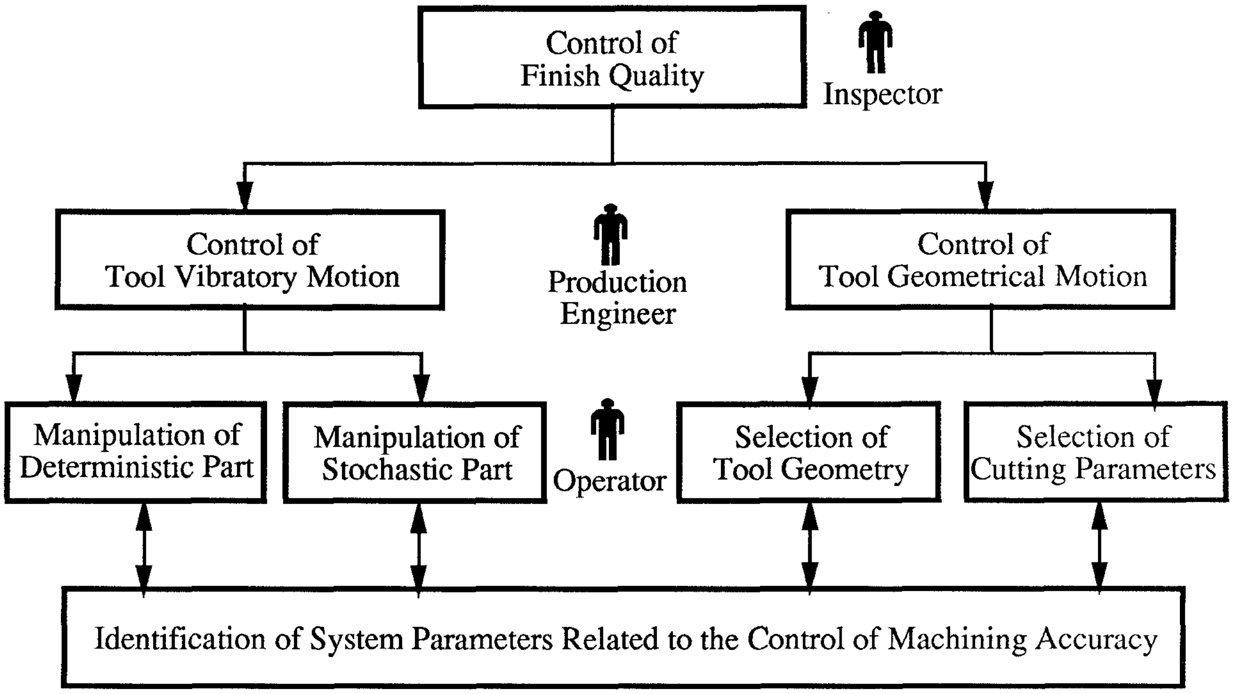
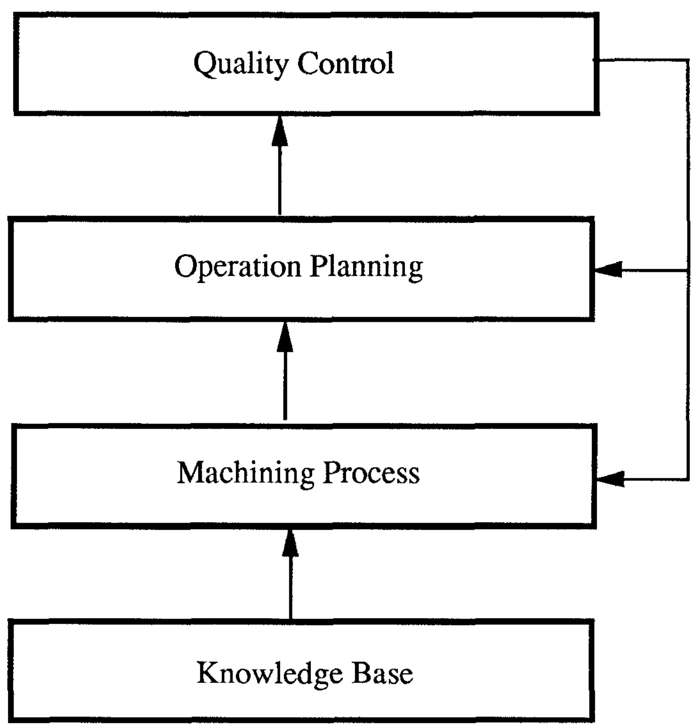


Figure 1c Sinusoidal Tool Vibratory Motion

Figure 1 Machine Surface Generation



(a) Analysis Hierarchy



(b) Computer-Based Framework

Figure 2 Basic Methodology Used for the Control of Machining Accuracy

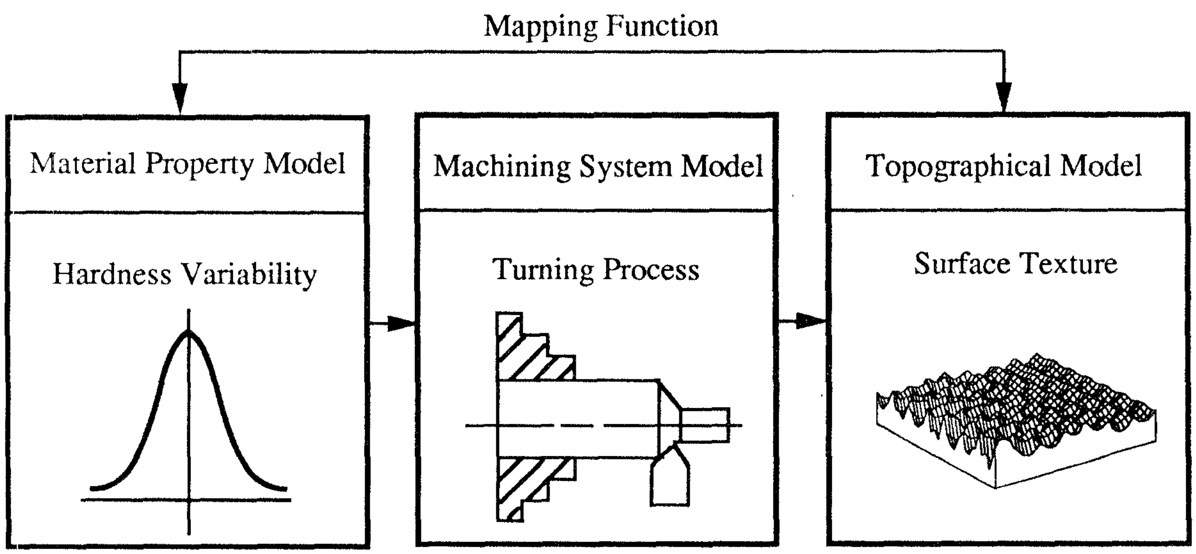


Figure 3 Model-Based Framework

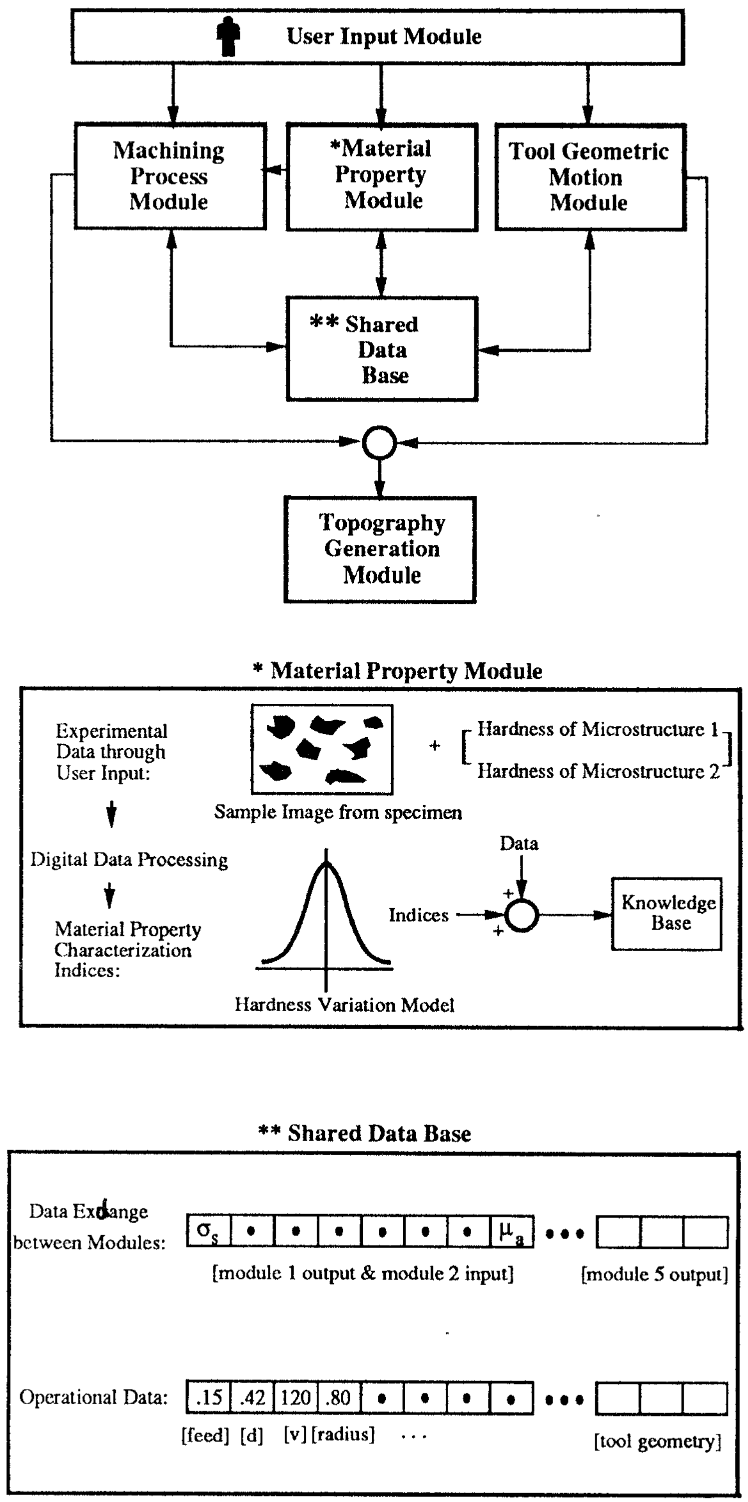
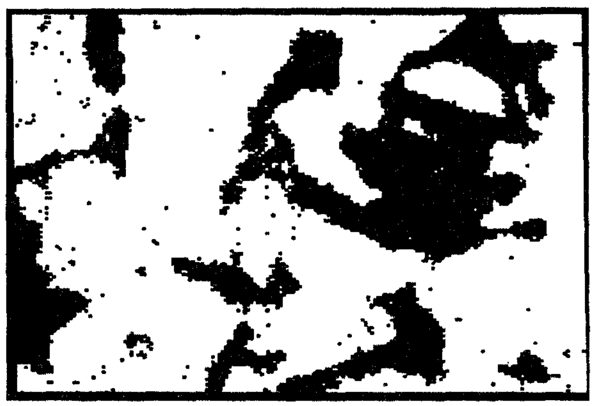


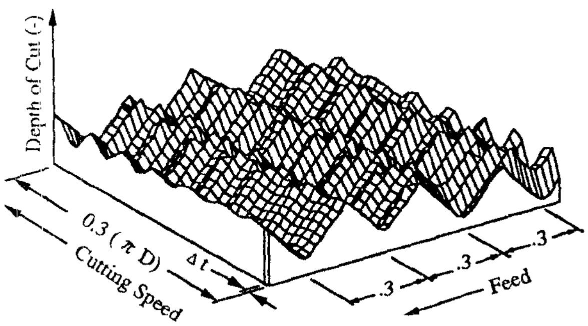
Fig. 4 Framework of the Developed Software

(a) Sample Image Taken from Specimen
(before Contrast Enhancement)

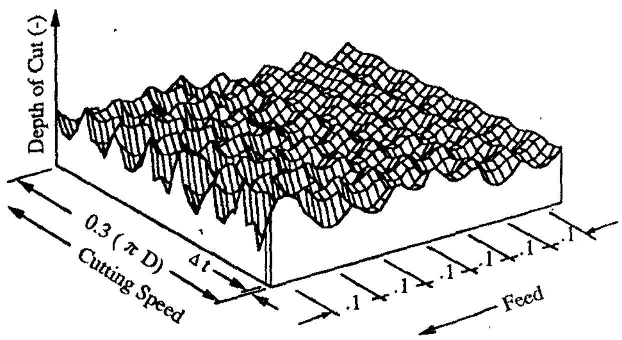


(b) Sample Image Taken from Specimen
(after Contrast Enhancement)

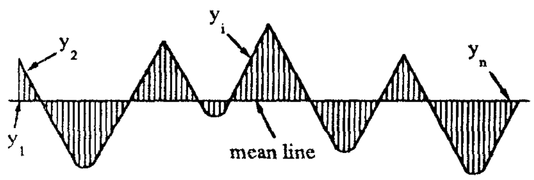
Fig. 5 Experimental Microstructural Analysis



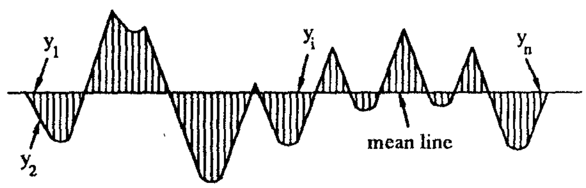
Surface Roughness $R_{a\,mean} = 4.2\ \mu m$
Standard Deviation $\sigma_{R_a} = 0.7\ \mu m$



Surface Roughness $R_{a\,mean} = 3.4\ \mu m$
Standard Deviation $\sigma_{R_a} = 1.8\ \mu m$

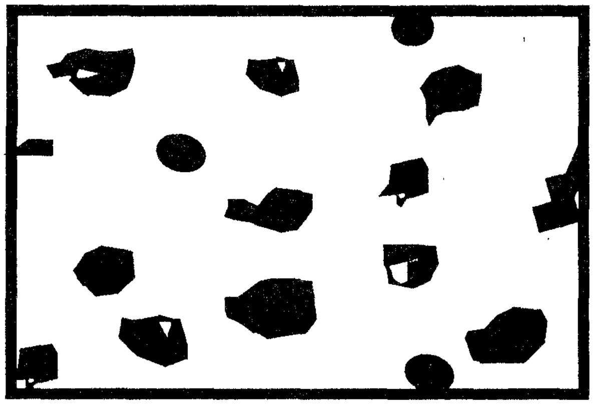


Surface Roughness Profile for Feed = 0.3 mm/rev

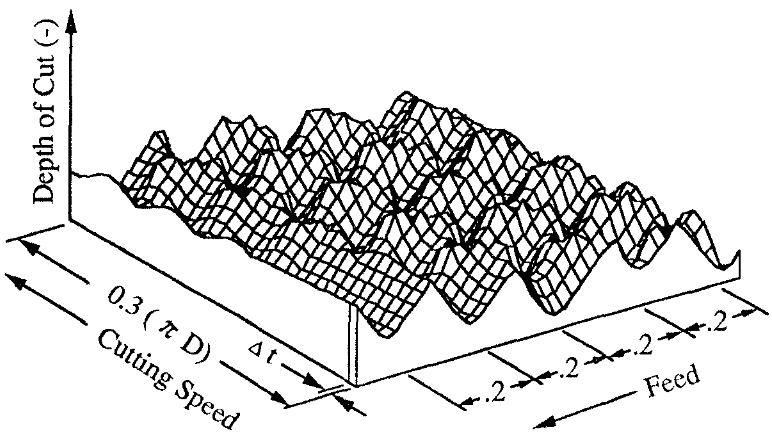


Surface Roughness Profile for Feed = 0.1 mm/rev

Figure 6 Simulated Surface Topographies



(a) Microstructures after Spherized Treatment



Surface Roughness $R_a = 2.4\ \mu m$

Standard Deviation $\sigma_a = 1.7\ \mu m$

Figure 7b. After Heat Treatment

Fig. 7 Effect of Heat Treatment on Topography Generation

Table 1 Calculated R_a Values at Twelve Selected Sections Taken from the two Surface Topographies (Figure 6)

Section Number	R_a Value (μm) Feed = 0.10 mm/rev	R_a Value (μm) Feed = 0.30 mm/rev
1	4.70	4.07
2	2.10	3.90
3	2.38	3.96
4	1.80	3.97
5	4.96	4.11
6	2.27	3.99
7	2.34	4.04
8	4.91	6.56
9	8.06	4.11
10	2.40	4.06
11	2.77	4.03
12	1.87	4.04
Average $R_{a\ mean}$	3.38 (μm)	4.24 (μm)
Standard Deviation σ_{Ra}	1.82 (μm)	0.70 (μm)