TECHNICAL
RESEARCH
REPORT

SYSTEMS
RESEARCH
CENTER

*Supported by the National Science Foundation Engineering Research Center Program (NSFD CD 8803012), Industry and the University*

# Dynamic Visualization of the Surface Texture Formed During Machining

*by G.M. Zhang, T.W. Hwang and J.F. Song*

TR 91-3

# Dynamic Visualization of the Surface Texture Formed During Machining

G. M. Zhang and T. W. Hwang
Mechanical Engineering Department and Systems Research Center
University of Maryland at College Park
College Park, MD 20742

J. F. Song
National Institute of Standards and Technology
Gaithersburg, MD 20899

## Abstract

This paper presents a new methodology to study the properties of machined surfaces. A conceptual framework designed for dynamically visualizing the surface texture formed during machining is proposed. By integrating material science, machining science, and metrology science, the framework provides a systematic approach to investigate the mechanism of surface irregularity formation during machining. Studying the variability of basic material properties in micro-scale and relating this information to the surface texture formation during machining, this research provides a computer-based and comprehensive metrological system for industrial control and diagnostics of the surface quality during machining.

## I. INTRODUCTION

The ever increasing competition in the marketplace is forcing industries to seriously evaluate the design and manufacturing of their products. For those products having components operating in a tribological environment, the surface quality is one of the major concerns. Reliability and durability of the product are directly influenced by the friction and wear of the contact surfaces.

In quality engineering, control of the surface quality includes the design, manufacturing, and inspection of the surface texture. Study of the relationship between surface finish and functional properties of mechanical parts has been a focus of research for sometime. Investigation of surface roughness effects on the formation of solid lubricant films established certain criteria for the design of surface texture to control the dynamic lubrication of sliding surface contacts [1-2]. Progress in surface texture measurement and the appraisal of surface topography has been made to provide industries with effective methods to assess and appraise the surface topographies formed during machining [3-6]. Control of the formation of surface texture during machining has been the long-standing endeavor of the machine tool industry and the manufacturing community [7-11]. It involves the control of both the static and dynamic tool path errors while a mechanical part is being machined. Results from previous research have revealed that the tool geometry and machining parameters are the main factors relating to the formation of the deterministic portion of surface texture. By providing precise spindle and feed mechanisms and controlling the structural dynamics of a machine tool, precision engineering has offered methods to control the surface texture formed during machining. However, formation of the surface irregularities caused by random tool motion during machining has not been well understood. Evaluation and control of the stochastic portion of surface texture still remain to be investigated. A recent study indicated that the nonhomogeneity of basic material properties, such as hardness, could be one of the major sources to excite random tool motion during machining [12]. Interest has been stirred to establish a mapping function between the variability of standard material properties and the formation of surface irregularities through the evaluation of the random tool motion during machining. Consequently, such work could resolve the problem of relating surface functional requirements and pertinent machining parameters.

This paper presents a new methodology to dynamically visualize the surface texture generated during machining. A conceptual framework for the visualization is proposed. From a systems engineering perspective, the framework identifies the major components and their interrelations contributing to the generation of surface texture. A stochastic approach is used to quantitatively characterize the random nature of a machined surface through the evaluation of random tool motion. By integrating material science, machining science, and metrology science, the framework provides a systematic approach to reveal the mechanism of surface irregularity formation during machining. A prototype model is developed to predict surface height measurement of a machined surface. To validate the proposed methodology and test validity of the developed framework, a comparison is made between two topographies of a machined surface, one of which is obtained from direct measurement and the other is constructed based on the prediction of the prototype system. The significance and potential applications of the developed framework, serving as a computer-based and comprehensive metrological system, are presented through discussion of the results.

## II. FRAMEWORK OF SURFACE TEXTURE VISUALIZATION

### 2.1 Characteristics of the Surface Texture Formed during Machining

Regarding the surface texture generation during machining, Fig. 1a presents a pictorial illustration of a mechanical part being machined on a lathe. From the kinematic point of view, the two motions necessary to generate a machined surface are the rotatory motion of the workpiece (cutting speed) and the translatory motion of the tool (feed) while the tool and workpiece maintain a fixed relative position (depth of cut) with each other. Ideally, the surface texture formed during machining should be determined by the two motions and tool geometry. Figure 1b presents such an ideal surface texture in a three-dimensional view through computer simulation. Note the three dimensions in Fig. 1b which represent the directions related to feed, cutting speed, and depth of cut, as indicated in Fig. 1a. However, the surface texture of a machined surface observed on the shop floor is significantly different from the ideal surface texture shown in Fig. 1b.

To demonstrate the difference, a workpiece of low carbon steel was machined on a lathe. The three cutting parameter settings used during machining were identical to those used in the computer simulation to construct the surface topography shown in Fig. 1b . A TALYSURF 6 surface profilometer was used to measure surface profiles from the machined surface. A total of twenty five surface profiles were collected within a rectangular area of 4.8 x 4.0 mm. All the profiles are in parallel and separated from each other by 0.2 mm. Figure 1c is a plot of the assembly of the measured surface profiles, representing the surface topography measured from a machined surface. Comparing the measured and simulated surface topographies indicates an increase in surface irregularities in the measured surface topography. Common sense dictates that these surface irregularities were generated as a result of the tool vibratory motion during machining, a motion which was not considered in the construction of the topography shown in Fig. 1b.

For quantitative comparisons, Fig. 2 presents two surface profiles. Each of them is taken from the simulated and measured topographies. As indicated in Fig. 2, roughness average, Ra, is used as an index for the comparison. The actual measured Ra value of 4.28 μm is significantly larger than the Ra value of 2.87 μm calculated from the simulated profile which is solely based on geometry of the tool outline. Table 1 lists the Ra values measured from the machined surface. The twenty five Ra values listed in the first column are measured within the rectangular area noted above. The measured Ra value varies among the twenty five Ra values with a mean and standard deviation equal to 4.20 and 0.09 μm, respectively. The additional twenty five Ra values listed in the second column are measured at randomly chosen locations on the machined surface. The associated mean and standard deviation are 4.22 and 0.32 μm, respectively. Comparing the mean and standard deviation with those listed in the first column shows a significant difference between the two standard deviations. The two mean values are similar. These observations indicate the necessity of taking profiles from the machined surface at various locations randomly chosen, and the need to apply statistical methods for a satisfactory appraisal of the surface topographies formed during machining.

### 2.2 Effect of Tool Motion on Surface Texture Formation

The motivation to dynamically visualize the surface texture formed during machining is to study the microstructure of machined surfaces, and quantify the relation between machining parameters and the machined surface irregularities for the purpose of controlling the quality of machined surfaces.

As illustrated in Fig. 1a, the surface texture formed is determined by the tool geometry and the tool motion during machining. The tool motion during machining may be decomposed into two parts, kinematic and vibratory motions. The kinematic motion of the tool during machining is determined by the cutting parameter settings. For example, the pitch of the tool spiral trajectory shown in Figs. 1a and 1b is equal to the selected feed in terms of the distance travelled by the tool during one revolution of the workpiece. The vibratory motion of the tool is caused by the generated cutting force, which excites the tool post structure to vibrate during machining. Conceptually speaking, the kinematic motion, incorporated with the tool geometry, characterizes a basic pattern of machined surface profiles. The vibratory motion explains the presence of surface irregularities, which are superimposed upon the basic pattern of machined surface profiles. Note that such superimposition introduces spatial relationships between the heights of the surface profiles taken at different locations. As we have witnessed in practice and as the data shown in Table 1 indicates, profile measurements vary across a machined surface.

### 2.3 Framework Architecture

For the characterization and quality control of machined surfaces, a conceptual framework is developed with focus on the visualization of the surface texture formed during machining. Figure 3 is the block diagram depicting the architecture of the framework. The framework consists of five modules, i.e., the user input module, the tool vibration module, the tool kinematics module, the surface texture generation module, and the surface characterization module. In the user input module, information related to the tool geometry specification, cutting parameter setting, and basic material properties is provided through the framework user. In the tool vibration module, the tool vibratory motion, both the deterministic and stochastic portions, is evaluated based on the machining operation system, which is represented by a mechanistic model. In the tool kinematics module, the spindle rotation and tool transversal movement(s) of the machine tool are combined to establish an undisturbed, or ideal, tool path during machining. This ideal tool path serves as a base trajectory on which surface irregularities caused by the tool vibratory motion will be superimposed. The surface texture generation module performs the superimposition, and at the same time, arranges each segment of the surface texture produced during machining into a specific location according to the time sequencing. This process dynamically visualizes the formation of the surface texture appearing on a machined surface. The surface characterization module is a post-processing module to calculate the characterization indices of surface quality such as roughness average, peak-to-valley, roundness, straightness, and cylindricity. The unique feature of the framework is to incorporate a quantitative evaluation of the random tool motion during machining into the surface texture visualization. The random tool motion is evaluated through microstructural analysis of the basic material properties and the cutting dynamics in microscale. The integration of the material science, machining science, and metrology science vividly reveals, in microscale, the mechanism of forming the surface texture during machining. It also offers a new approach to the description of machined surfaces in three-dimensional space characterized by the three machining parameters. Such a capability would be valuable for machining operation planning, especially in NC machining where the selection of the cutting parameters must be made in the programming stage.

## III. VISUALIZATION OF SURFACE TEXTURE

In general, evaluation of the tool vibratory motion during machining requires a mathematical model to describe the machining operation. This model serves as a function which maps a combination of the input entities, such as tool geometry, machining parameters, and workpiece material, to a quantitative representation of the tool vibratory motion. Accordingly, for the evaluation of the stochastic portion of the tool vibratory motion, or the random tool motion, the mapping function needs a quantitative description of random excitation in the input space. Without such a quantitative form of random excitation, the randomness observed in any roughness profiles and surface topographies would be explained only qualitatively. This section presents the process of visualizing the surface texture formed during machining with emphasis on qualification of the surface irregularities, especially, the random surface roughness, through the evaluation of random tool motion during machining.

## 3.1 Random Tool Motion during Machining

In machining science, the practically observed vibratory motion of the cutting tool during machining consists of two components, i.e., the deterministic and stochastic components. The deterministic component is responsible for the machining action due to the application of nominal settings of the input entities, such as the tool geometry, and machining parameters. Methods to evaluate the deterministic component can be found [12-13]. However, evaluation of the stochastic component of the tool vibratory motion during machining has posed a problem to be resolved due to the complexity, such as the sources and characteristics of random excitation present during machining.

Thanks to the advancement of computerized microstructural analysis in the material science, the distribution of microhardness in the material to be machined has been recognized as an important factor in causing random tool motion. Figure 4 illustrates how both the amount of the microstructures and their scale contribute to the presence of random excitation during machining. As indicated in Figs. 4a and 4b, there exist two types of microstructures in the material. Assume that the spherical parts in Fig. 4a and the rectangular parts in Fig. 4b represent the microstructures associated with a high hardness value. The white parts in Figs. 4a and 4b represent the microstructures associated with a low hardness value. The degree of nonhomogeneity of the microhardness distribution in the material, which directly affects to random tool motion, depends on the following three factors.

1. The difference in microhardness value between the two microstructures. It is evident that the degree of nonhomogeneity increases as the difference increases. The degree of nonhomogeneity would vanish when the difference approaches zero.

2. The size and shape of the microstructures present in the material. Common sense dictates that microstructures with small sizes and spherical shapes tend to be homogeneous in nature.

3. The variation of the ratio of the two microstructures within a given volume. A large variation of the ratio among individual volumes indicates a strong tendency toward nonhomogeneity. For example, divide the area shown in Fig. 4a into four equal subareas and calculate the four individual ratios ($r_1$, $r_2$, $r_3$, and $r_4$). Afterwards, divide the same area into two equal subareas and calculate the two individual ratios ( $R_1$ and $R_2$) . It can be expected that the variation among the four ratios ($r_1$, $r_2$, $r_3$, and $r_4$) would be significantly larger than the difference between $R_1$ and $R_2$. This indicates that large volumes may average out the ratio variation so as to diminish the degree of nonhomogeneity.

The effect of the nonhomogeneous hardness distribution in the material on the tool vibratory motion can be quantified through the cutting dynamics in microscale [14]. Figure 5 is an enlarged view of a turning operation. In microscale, the turning operation may be viewed as a process in which the cutting tool meets a set of microstructures instantaneously. To visualize the random tool motion during machining, divide the outside layer of the workpiece into a number of subdivisions, say n subdivisions. As indicated in Fig. 5, the geometrical shape of a subdivision is determined by the three machining parameters. A severe tool vibration can be anticipated when the tool meets a subdivision with an extreme microstructural ratio value in either the high or low side. Since the microstructural ratio of a subdivision varies randomly due to the nonhomogeneous hardness distribution, the tool exhibits random motion accordingly.

A quantitative approach to evaluate the random tool motion due to the nonhomogeneous hardness distribution and machining parameter settings has been developed [12]. As shown in Figs. 4a and 4b, the correlation coefficient function of the microhardness distribution, $\rho(r)$, is used to characterize the size, shape, and distribution of the microstructures. The correlation coefficient function of Fig. 4a, $\rho_1(r)$, is significantly different from that of Fig. 4b, $\rho_2(r)$, because they characterize two different microstructural distributions. Incorporating the three cutting parameters to account for the effect of the volume of a subdivision on the evaluation of random tool motion, the geometric shape function is formulated. Combining the correlation coefficient function and the geometrical shape function provides a quantitative description of the random excitation present during machining. The random excitation is represented by a normal distribution model with mean and variance as the two parameters characterizing the average and variation levels of the random excitation present during machining. For evaluation of the random tool motion, the mapping function, which describes the machining operation, is used to manipulate the magnitude of the random tool motion for a given instant random excitation.

As examples to demonstrate the evaluation of random tool motion, SAE 72 steel and 2021 aluminum alloy materials were machined on a lathe. Figure 6 presents their micrographs, correlation coefficient functions calculated from the micrographs, and simulated tool vibratory motions in a turning operation. Note that the magnitude of random tool vibration for machining the steel material is significantly larger than that for machining aluminium. This is due to the large difference in hardness between ferrite and pearlite structures, and the irregular shapes of the pearlite structures in the steel material. These two characteristics lead to a strong random excitation during machining. On the other hand, the precipitation of silicon in the aluminium alloy material results in hard spots and the $\alpha$ phase, a solid state of aluminium, functions as soft spots. The large difference in hardness between the $\alpha$ phase and the silicon precipitates might cause a severe random tool motion. However, the silicon precipitates are so small and uniformly distributed in the $\alpha$ phase that the cutting tool may not be able to sense the existence of hardspots during machining. Consequently, random tool vibration is significantly attenuated during the machining of aluminum alloy materials.

### 3.2 Surface Texture Visualization

The mechanism to form the surface texture during machining is to trace how the tool removes the material from the workpiece instantaneously. The evaluation of the tool vibratory motion provides an instant deviation of the tool motion away from its ideal, or undisturbed, tool path determined by the tool kinematic motion during machining. This makes it possible to identify the relative position between the workpiece and the tool at a given location on the machined surface. Regarding the turning operation, the surface texture formed during machining should be examined along both the circumferential and the axial directions of the workpiece.

Figure 7 presents an intuitive view to explain how the surface texture is formed on the workpiece circumference. The three points marked as A, B, and C represent the three cutting locations on the cutting edge of the tool. From the viewpoint of kinematics, points A, B, and C have an identical path trajectory, which is the tool vibratory motion about the ideal tool path indicated by the dashed straight line shown in Fig. 7. Consequently, the geometry of the surface texture formed on the circumference at a given instant should be a copy of the outline of the tool at a specific location. The surface texture along the axial direction of the workpiece, or the surface profile, is formed by a series of adjacent outlines of the cutting tool, as shown in Fig. 8. A pair of two neighboring tool outlines represents two specific tool positions during machining, which are separated by a time interval equal to the time needed for one revolution of the workpiece during machining. As a result, the surface texture formed during machining can be visualized as a dynamic process, in which the outlines of the cutting tool are concatenated on the workpiece circumference, and at the same time, each outline of the cutting tool links to that of the previous revolution, so as to form a surface profile in the axial direction. The deviation of the tool position from the ideal tool path results in the variation of the heights of the tool outline both on the circumference and along the axial direction of the workpiece.

To uniquely determine the surface texture formed during machining, it is necessary to know the coordinates of each of the individual points for a given surface profile, such as the one shown in Fig. 8. By examining the geometrical constraints indicated in Fig. 8, the coordinates of the intersection point between a pair of the two neighboring outlines can be calculated based on the following two equations.

$$(x_k - C_{kx})^2 + (y_k - C_{ky})^2 = R^2$$
$$(x_k - C_{(k+1)x})^2 + (y_k - C_{(k+1)y})^2 = R^2 \qquad (1)$$
$$\text{for } k = 1,2,\ldots, (j-1)$$

where $R$ = tool nose radius,

$x_k$ = coordinate of the $k^{th}$ intersection point in the direction of feed, and

$y_k$ = coordinate of the $k^{th}$ intersection point in the direction of depth of cut.

The coordinates of the other points on the surface profile can be determined by referring to the coordinates of the relevant intersection points. For example, the coordinates of point D in Fig. 8, which is next to intersection point C, can be written in $x_k + \Delta x$ and $y_k + \Delta y$ where $\Delta x$ and $\Delta y$ are constrained by Eq. (1) because point D is located on the circle. A surface profile can be uniquely visualized in a two dimensional space when the coordinates of all the points are known. Note that the two dimensions are related to the directions of feed and depth of cut. The method to identify the surface profile in a two-dimensional space forms a basis to build the surface texture generation module of the framework illustrated in Fig. 3. By constructing the two dimensional surface profiles formed at different time instants during machining and linking them together by the order of time, the framework developed is capable of displaying the surface texture formation during machining dynamically.

## 3.3 Experimental Verification

To validate the basic methodology used in developing the framework for the visualization of surface texture formed during machining, experiments were carried out and the experimental results were compared with the results derived from the developed framework. The experimental work carried out for the comparison consists of:

1. Performing the microstructural analysis. The main purpose is to identify the microstructural distribution in the material to be machined. This analysis forms a basis for the determination of random tool motion. For doing so, a sample was taken from an SAE 72 steel bar to be machined. After polishing and etching, the sample was placed under a JEOL scanning electronic microscope to identify the type of microstructure at individual locations.

2. Machining the SAE 72 steel bar. The bar diameter was 80 mm and the length was 300 mm. The SAE 72 steel bar was machined on a Placemaker lathe. The following machining parameter settings were used.

   Cutting data: feed = 0.23 mm/rev, depth of cut = 0.5 mm, and spindle speed = 470 rpm.
   Tool geometry: nose radius = 0.8 mm, rake angle = $0^{o}$, and lead angle = $60^{o}$.

3. Taking surface profiles. A Talysurf 6 surface profilometer was used to measure the machined surface profiles along the axial direction. The measured surface profiles were positioned in parallel to form a surface topography, as shown in Fig. 9a.

Based on the proposed conceptual framework, a prototype system was developed in this work. A mathematical model, representing the turning machining operation, was used to simulate the tool vibratory motion in the framework. By modeling the random excitation based on the identified microstructural distribution in the material being machined, the prototype system is capable of evaluating the random tool motion during machining. Incorporating the tool geometry with the tool motion, the prototype system then visualizes the dynamic process of the surface texture formed during machining. The surface topography shown in Fig. 9b was constructed through the computer visualization. For the purpose of comparison, the machining parameter settings and tool geometry used in the prototype system were identical to those used in the experimental work.

By comparing the two surface topographies shown in Figs. 9a and 9b, a general similarity between them can be well recognized. Examining these surface topographies, the common characteristics are the waviness of the surface texture on the circumference which is caused by tool vibration, and the arc-chain pattern along the axial direction as a result of the tool kinematic motion. Although these findings from examination of the topographies are qualitative, the validity of the proposed methodology to visualize the surface texture formed during machining has been strongly confirmed.

## IV. DISCUSSION OF RESULTS

As demonstrated by the results presented above, the surface texture revealed by the developed framework closely resembles the surface texture observed directly from the machined surface.

A quantitative comparison is present to indicate the accuracy of the surface texture simulated through the visualization process. The roughness average ($R_a$), the root mean square of roughness ($R_q$), and the mean of the peak to valley heights ($R_{tm}$), which are most used, are selected as the surface roughness characterization indices for the comparison. Table 2 presents the numerical data. The data listed in Part 1 was obtained from the direct measurement for machining the SAE 72 steel. The data listed in Part 2 are the $R_a$ values calculated from the surface profiles through visualization for machining the SAE 72 steel. An observation can be made that the values of $R_a$, $R_q$, and $R_{tm}$ listed in Part 1 are well matched with those of Part 2. For example, the mean values of $R_a$, $R_q$, and $R_{tm}$ obtained from the measurement are 4.22 μm, 4.90 μm, and 18.91 μm. The mean values of $R_a$, $R_q$, and $R_{tm}$ predicted by the prototype system are 4.10 μm, 4.98 μm, and 16.58 μm. The measured and predicted values of $R_a$ and $R_q$ are fairly well matched from the viewpoint of statistics. These observations indicate that a careful calibration to set the system parameters of the developed framework is necessary to ensure the accuracy of the surface texture visualization.

However, discrepancies have been observed when comparing the measured values of $R_{tm}$ and $\sigma_{Rtm}$ with the simulated values of $R_{tm}$ and $\sigma_{Rtm}$. These values are different if statistical significance tests are performed. In fact, the observed discrepancy between the measured mean value of $R_{tm}$ (18.91 μm) and the simulated mean value of $R_{tm}$ (16.58 μm) is consistent with the observation that the depth of the v-shaped surface texture in the measured topography (Fig. 9a) seems deeper than that in the simulated topography (Fig. 9b). To analyze the discrepancy, refer to Fig. 7 where the geometry of the surface texture through visualization is a copy of the tool outline because all points on the cutting edge have an identical travelling trajectory during machining. Figure 10 depicts three profiles taken on the circumference of the surface produced during the machining of the SAE 72 steel. They represent the actual travelling trajectories of the three cutting points A, B, and C during machining. Comparing the three trajectories, they all have the similar waviness pattern, indicating the inherent relation between tool vibration and the surface texture formation during machining. However, the magnitudes of the three trajectories are not equal. They vary from 10.5 μm at point A to 12.4 μm at point C. This magnitude variation, which has not been taken into consideration during the computer visualization, could be an important factor to cause the observed discrepancy. The second factor related to the observed discrepancy could be the deception of the geometrical shape of the formed surface texture during the recovery of elastic-plastic deformation, which has also been ignored during the computer visualization. As shown in Fig. 7, the contact deformation of the workpiece and tool materials, both elastic and plastic, develops during machining. Because the hardness of the workpiece material is relatively low with respect to the hardness of the tool material, the contact deformation is mostly on the workpiece side. At point C, plastic deformation is superior to elastic deformation because of the high pressure exerted by the cutting tool during machining, and a severe work hardening of the workpiece material caused by the tool sliding action during machining. As a result, the plastic deformation at point C sustains the tool path trajectory with little distortion caused by the recovery of elastic deformation. On the other hand, the plastic deformation at point A seems not as strong as that at point C. Consequently, the recovery of the elastic deformation at point A after the cutting tool travels along the circumference is more significant than the elastic recovery at point C. The effect of the elastic recovery on the deception of the surface texture formed during machining can be further confirmed by observing the variation of the vertical distance between point A and point C among the 25 measured profiles. From the geometrical point of view, the vertical distance between point A and point C, or the distance marked as dy in Fig. 7, should be equal to 1.40 μm. However, the measured vertical distance value, as illustrated in Fig. 10, varies from one profile to another with the largest value equal to 7.32 μm obtained in profile 13 ($dy_{13}$) and the smallest value equal to 0.8 μm obtained in profile 1 ($dy_1$). The measured vertical distance in profile 7 ($dy_7$) is equal to 4.21μm, representing the mean value of the twenty five measured vertical distances. This mean value is significantly larger than the predicted value (1.40 μm), indicating that the slope of the line connecting point A and point C will be significantly larger than the slope predicted based on the tool geometry, as indicated in Fig. 9c. In order to rectify the surface texture constructed through the computer visualization, a study, which employs finite element method, has been conducted to quantitatively evaluate the stress and strain distribution in the contact area. It is expected that, based on the stress and strain distribution, a format to perform a pre-adjustment of the tool outline for the compensation of the vertical distance variation of the surface texture, and to modify the path trajectories of individual cutting points along the cutting edge will be developed for an accurate prediction of the surface texture formed during machining.

At the present stage, the framework developed for the surface texture visualization serves as a prototype model of the computer-based metrological system for industrial control and diagnostics of the quality of machined surfaces formed during machining. The developed framework clearly depicts how the parameters of a machining operation system affect the surface texture formation during machining, thus resolving the problem of relating the surface functional requirements and pertinent manufacturing parameters. For example, through evaluating the effect of microstructures in the material to be machined, the framework is capable of advising the improvement of surface texture by controlling the size, shape, and segregation of the microstructures in the material. Therefore, the visualization of surface texture formed during machining has linked the design of surface texture to meet the functionality in a tribological environment to the control of the surface texture actually formed during manufacturing. The development of this computer-based framework has made a significant contribution to the quality control of machined surfaces, especially in an environment of automated production. For NC machining, the developed framework can be used as a simulation tool to perform an off-line optimization in setting machining parameters during the programming stage. The availability of the data base generated through visualization makes it possible to construct a surface profile either on the circumferential, or on the axial, direction of the workpiece, thus characterizing the spatial relationships between profile heights which, basically, differ with direction. As a result, the proposed framework could be used to predict the finish quality of a machined surface, instead of taking actual measurements from the machined surface. This capability would facilitate assessing the finish quality of holes with a small diameter and a large ratio of length to diameter. Such assessments usually pose a serious technical problem on the shop floor. By providing information on the variation of surface profiles taken at different locations on a machined surface, the proposed framework fits the need to guide the quality inspection by suggesting the number of traces to be taken on the machined surface being inspected. By combining this framework with sensor technology to detect the on-line tool vibration during machining, the framework may become an essential part in performing the in-process inspection

## V. CONCLUSIONS

1. The work presented in this paper successfully demonstrates a conceptual framework and the development of a prototype computer-based system for the visualization of surface texture formed during machining. The topography of a machined surface through computer visualization, confirmed by experimental verification, vividly depicts the dynamic process of surface texture formation during machining. The proposed framework offers a great potential of industrial applications in controlling the finish quality.

2. The proposed methodology is built through the integration of three scientific branches, i.e., material science, machining science and metrology science. Considering the variability of basic material properties as a major source of random tool motion, the tool vibratory motion is quantitatively evaluated in microscale. Such an evaluation bridges the gap between the control of surface functional requirement and the control of pertinent manufacturing parameters. The study of the microstructure of machined surfaces through the analysis of cutting dynamics in micro-scale represents an innovative approach to establishing hardness variability as one of the standard materials properties for machining.

3. The computer-based prototype system for the visualization of surface texture is capable of generating the data representing a machined surface in a three-dimensional space characterized by the three machining parameters, i.e., depth of cut, feed, and cutting speed. The uniqueness of this data base is that it clearly defines the spatial relationships as a whole, rather than as a set of parallel profiles. As demonstrated in this paper, this information is very useful for guiding the control of finish quality on the shop floor. If an accurate calibration of the system parameters is made, the developed prototype system can be used

as a comprehensive metrological system for industrial control and diagnostics of the surface quality. This prototype system may also become an important component of a quality assurance system to perform in-process inspection for the certification of the machining process.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the Systems Research Center at the University of Maryland at College Park under Engineering Research Centers Program: NSFD CDF 8803012. They wish to thank Professor W. L. Fourney, Chairman of the Mechanical Engineering Department, for his valuable support in conducting this work. They express gratitude to Dr. T. V. Vorburger at the National Institute of Standards and Technology for suggesting the importance of establishing hardness variability as a standard materials property for machining.

REFERENCES

1. Whitehouse, D. J., Vanherck, P., deBruin, W., and vanLuttrervelt, C. A., "Assessment of Surface Typology Analysis Techniques in Turning," Annals of the CIRP, Vol. 23/2, 1974, pp. 265-282.
2. Stout, K. J. and Davis, E. J., "Surface Topography of Cylinder Bores: the Relationship between Manufacture Characterization and Function," Journal of Wear, Volume 95, 1984, pp. 111-125.
3. Reson, R. E., "Progress in the Appraisal of Surface Topography during the First Half-Century of Instrument Development," Wear, Vol. 57/1, 1979, pp. 1-16.
4. Vorburger, T. V., "Measurements of Roughness of Very Smooth Surfaces," Annals of the CIRP, Vol. 36/2, 1987, pp. 503-509.
5. Scott, P. J., "Development in Surface Texture Measurement," Journal of Surface Topography, Volume 1/1, 1988, pp. 153-163.
6. Song, J. F., "Random Profile Precision Roughness Calibration Specimens," Surface Topography, Vol. 1/1, 1988, pp. 303-314.
7. Sata, T. "Surface Finish in Metal Cutting," CIRP Annalen, XII, 1963, pp. 190-197.
8. Babin, T. S., Sutherland, J. W., and Kapoor, S. G., "On the Geometry of End Milled Surfaces," Proceedings of the 14th North American Manufacturing Research Conference, 1986, pp. 168-176.

9. Davis, E. J., Sullivan, P. J., and Stout, K. J., "The Application of 3-D Topography to Engine Bore Surfaces," Journal of Surface Topography, Volume 1/1, 1988, pp. 63-85.
10. Zhang, G. M., S. Yerramareddy, S., Lee, S. M., and Lu, S. C-Y., "Simulation of Surface Topography Formed during the Intermittent Turning Process," DSC-Vol. 18, 1989 ASME Winter Annual Meeting, pp. 11-18.
11. Song, J. F. and Vorburger, T. V., "Standard Reference Specimens in Quality Control of Engineering Surfaces," to be published.
12. Zhang, G. M., "Dynamic Modeling and Dynamic Analysis of the Boring Machining System," Ph.D. Thesis, University of Illinois at Urbana-Champaign, January, 1986.
13. Kline, W. A., DeVor, R. E., and Shareef, I. A., "The Prediction of Surface Accuracy in End Milling," Journal of Engineering for Industry, Tans. ASME, Vol. 104, 1982, pp. 272-278.
14. Zhang, G.M. and Hwang, T. W., "Analysis of the Cutting Dynamics in Microscale," PED-Vol. 43, 1990 ASME Winter Annual Meeting, pp. 25-37.

## List of Tables

Table 1 Measured Ra Values on a Surface of Turned Steel Bar

| Trace No. | Taken in a Box Ra (μm) | Randomly Taken Ra (μm) |
|---|---|---|
| 1 | 4.38 | 4.54 |
| 2 | 4.02 | 4.38 |
| 3 | 4.26 | 4.60 |
| 4 | 4.14 | 4.54 |
| 5 | 4.36 | 4.21 |
| 6 | 4.14 | 4.03 |
| 7 | 4.12 | 4.10 |
| 8 | 4.10 | 3.65 |
| 9 | 4.10 | 4.25 |
| 10 | 4.26 | 4.40 |
| 11 | 4.18 | 3.80 |
| 12 | 4.20 | 3.74 |
| 13 | 4.31 | 4.28 |
| 14 | 4.12 | 4.51 |
| 15 | 4.28 | 4.73 |
| 16 | 4.30 | 4.64 |
| 17 | 4.32 | 4.08 |
| 18 | 4.25 | 4.10 |
| 19 | 4.17 | 3.91 |
| 20 | 4.18 | 4.54 |
| 21 | 4.13 | 4.52 |
| 22 | 4.17 | 3.64 |
| 23 | 4.20 | 4.01 |
| 24 | 4.22 | 4.06 |
| 25 | 4.21 | 4.18 |
| Mean | 4.20 | 4.22 |
| Std. | 0.09 | 0.32 |

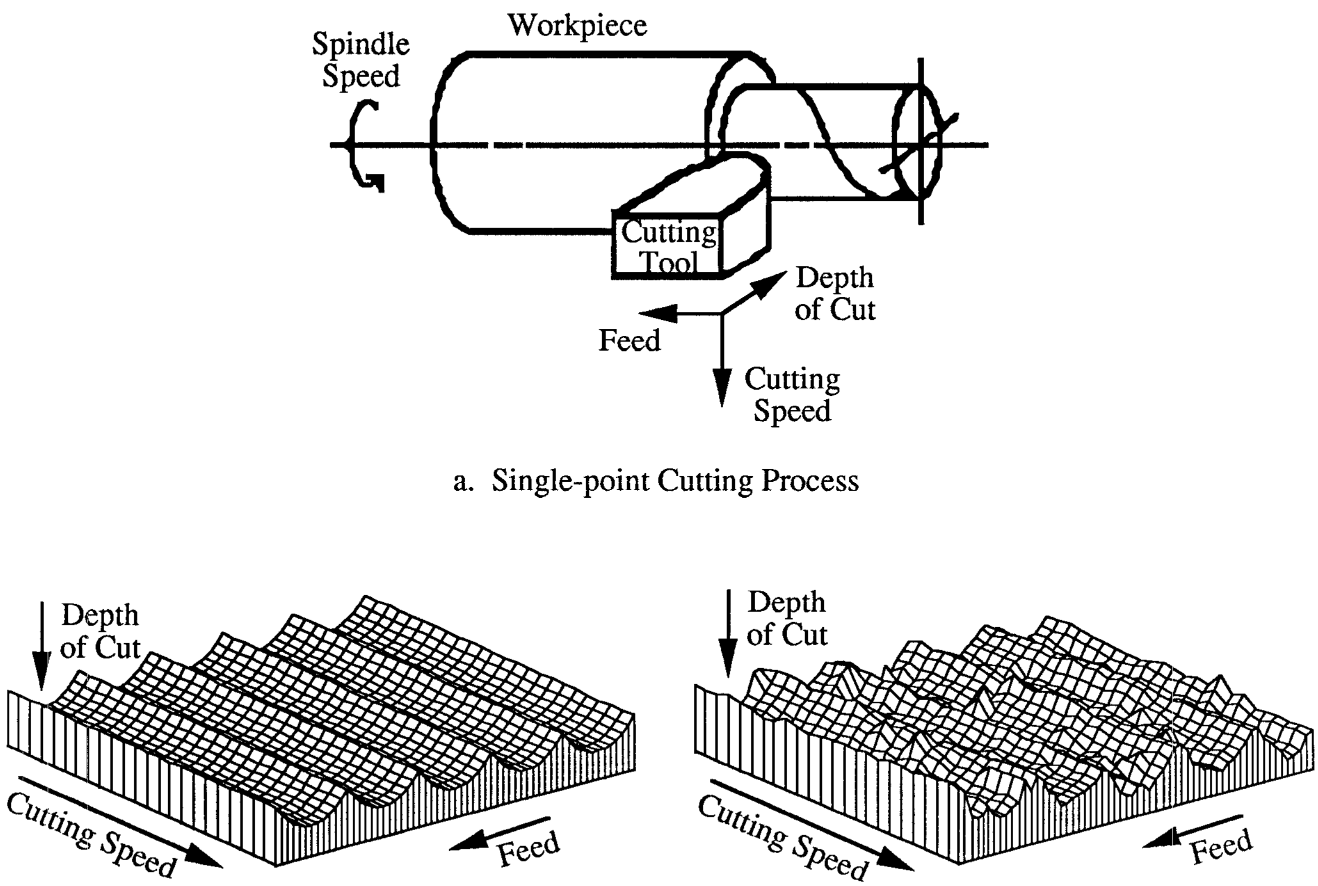
* Traversing length = 4 mm, ISO (2CR) filter, cut off length = 0.8 mm.

Table 2 Comparison of the Numerical Values of Three Roughness Indices

| | Part 1<br>Measured Surface Indices | | | Part 2<br>Simulated Surface Indices | | |
|---|---|---|---|---|---|---|
| | $R_a$ (μm) | $R_q$ (μm) | $R_{tm}$ (μm) | $R_a$ (μm) | $R_q$ (μm) | $R_{tm}$ (μm) |
| | 4.54 | 5.37 | 21.53 | 4.46 | 5.34 | 17.85 |
| | 4.38 | 4.90 | 17.83 | 4.39 | 5.55 | 16.98 |
| | 4.60 | 5.27 | 20.33 | 4.12 | 4.98 | 16.17 |
| | 4.54 | 5.27 | 20.23 | 3.87 | 4.68 | 16.62 |
| | 4.21 | 4.70 | 17.43 | 4.38 | 5.41 | 18.36 |
| | 4.03 | 4.56 | 17.23 | 4.28 | 5.18 | 18.34 |
| | 4.10 | 4.55 | 17.13 | 3.70 | 4.46 | 14.87 |
| | 3.65 | 4.12 | 17.03 | 4.19 | 5.00 | 17.07 |
| | 4.25 | 4.82 | 18.73 | 4.50 | 5.43 | 17.64 |
| | 4.40 | 5.09 | 20.93 | 3.80 | 4.56 | 16.10 |
| | 3.80 | 4.33 | 16.63 | 3.99 | 4.81 | 16.47 |
| | 3.74 | 4.28 | 17.43 | 3.98 | 4.85 | 16.42 |
| | 4.28 | 4.95 | 19.43 | 3.82 | 4.68 | 16.61 |
| | 4.51 | 5.05 | 18.93 | 4.40 | 5.38 | 16.84 |
| | 4.73 | 5.43 | 20.43 | 4.28 | 5.26 | 15.79 |
| | 4.64 | 5.40 | 20.93 | 4.10 | 4.94 | 16.50 |
| | 4.08 | 5.35 | 19.83 | 3.83 | 4.69 | 16.37 |
| | 4.10 | 5.34 | 19.83 | 3.96 | 4.77 | 16.04 |
| | 3.91 | 5.56 | 22.63 | 4.45 | 5.39 | 18.29 |
| | 4.54 | 5.07 | 18.63 | 4.49 | 5.40 | 15.91 |
| | 4.52 | 5.12 | 18.43 | 3.96 | 4.76 | 16.76 |
| | 3.64 | 4.10 | 16.03 | 3.66 | 4.38 | 14.79 |
| | 4.01 | 4.49 | 17.63 | 3.97 | 4.82 | 15.93 |
| | 4.06 | 4.53 | 17.83 | 4.21 | 5.02 | 16.18 |
| | 4.18 | 4.84 | 19.73 | 3.92 | 4.76 | 15.72 |
| Mean | 4.22 | 4.90 | 18.91 | 4.11 | 4.98 | 16.58 |
| Std. | 0.32 | 0.44 | 1.70 | 0.26 | 0.34 | 0.95 |

* Traversing length = 4 mm, ISO (2CR) filter, cut off length = 0.8 mm.

List of Figures




a. Single-point Cutting Process

b. Ideal Surface Texture

c. Measured Surface Texture

Fig. 1 Illustration of a Machining Process and Surface Texture Formation during Machining

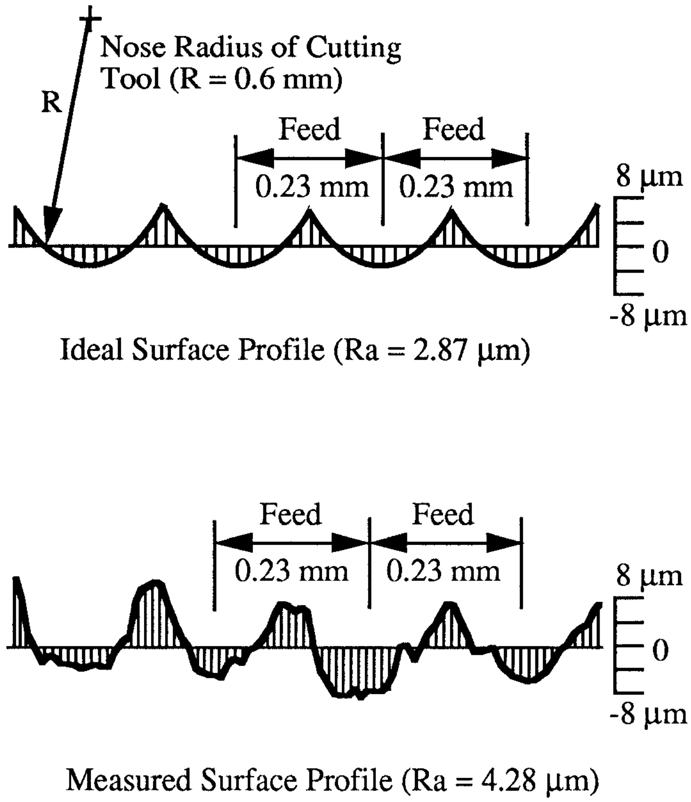



Fig. 2 Comparison between an Ideal and Measured Surface Profiles

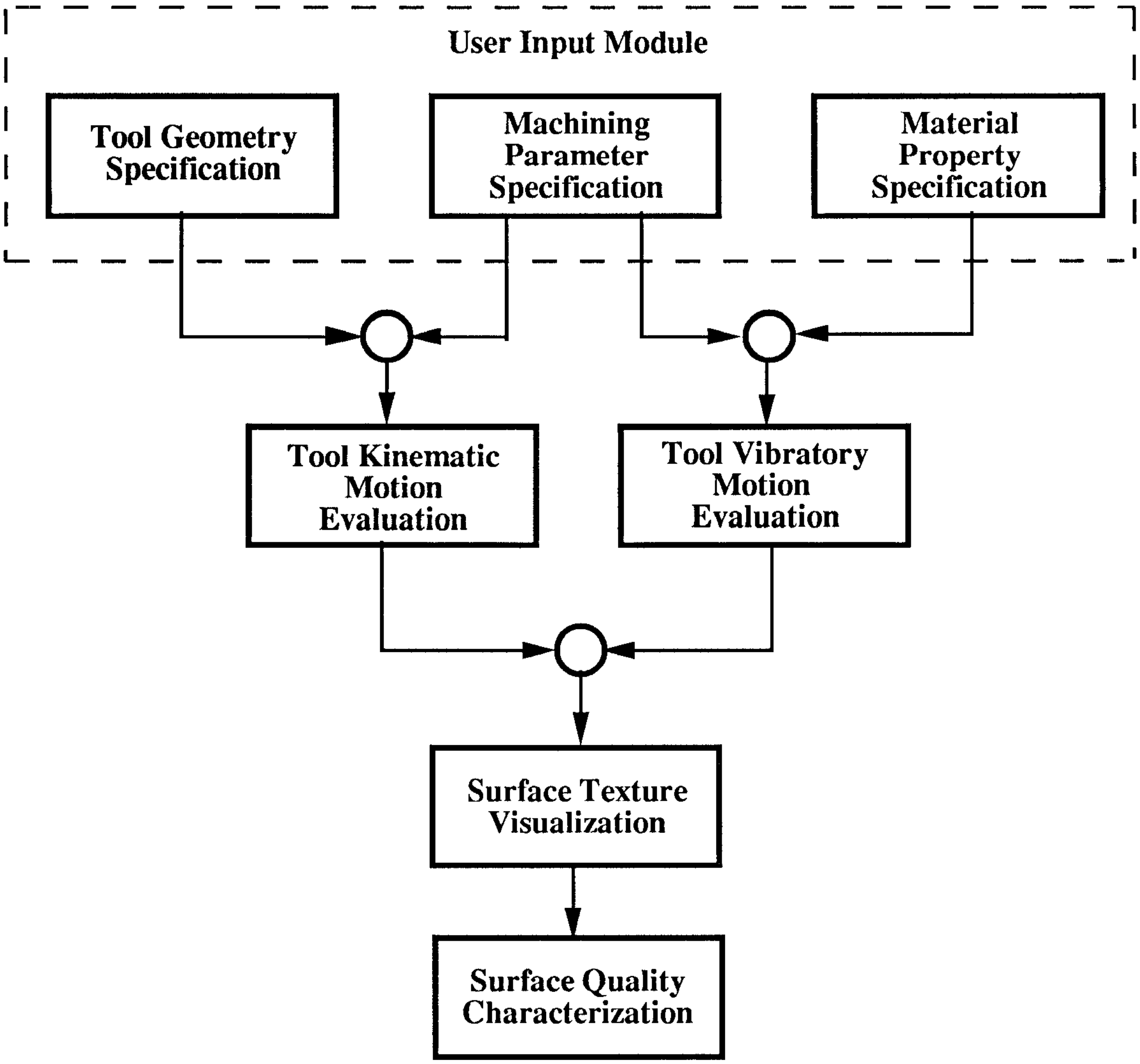
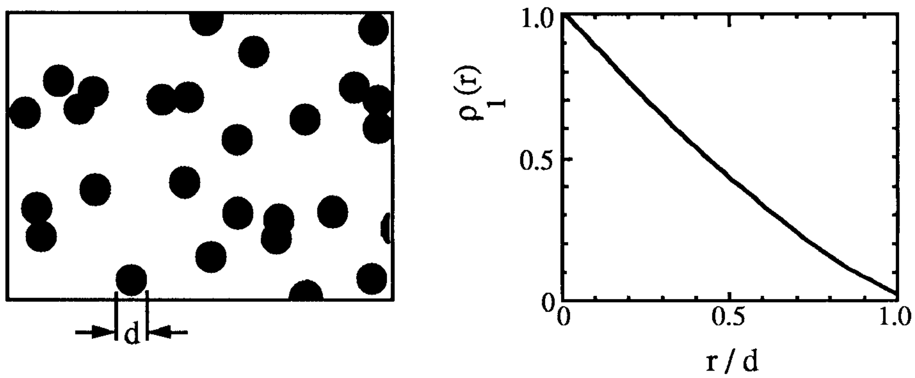
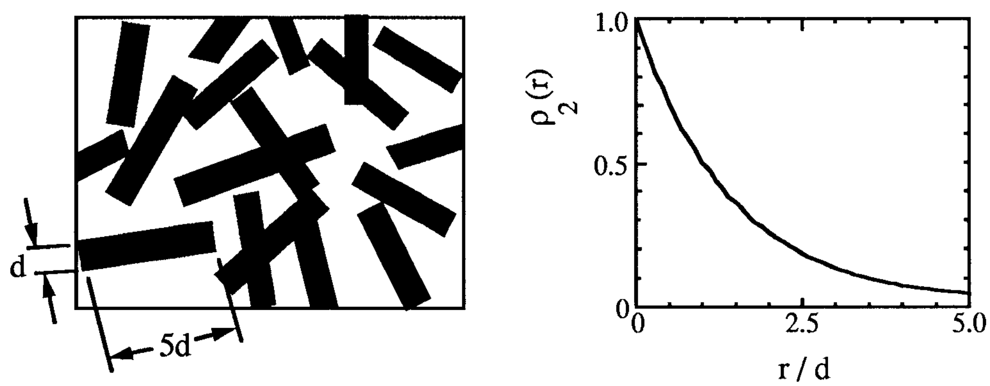



Fig. 3 Framework Architecture for Dynamical Visualization of Surface Texture




a. Correlation Coefficient Function (Spherical parts representing the microstructure associated with a high hardness value)




b. Correlation Coefficient Function (Rectangular parts representing the microstructure associated with a high hardness value)

Fig. 4 Microstructures and Correlation Coefficient Functions

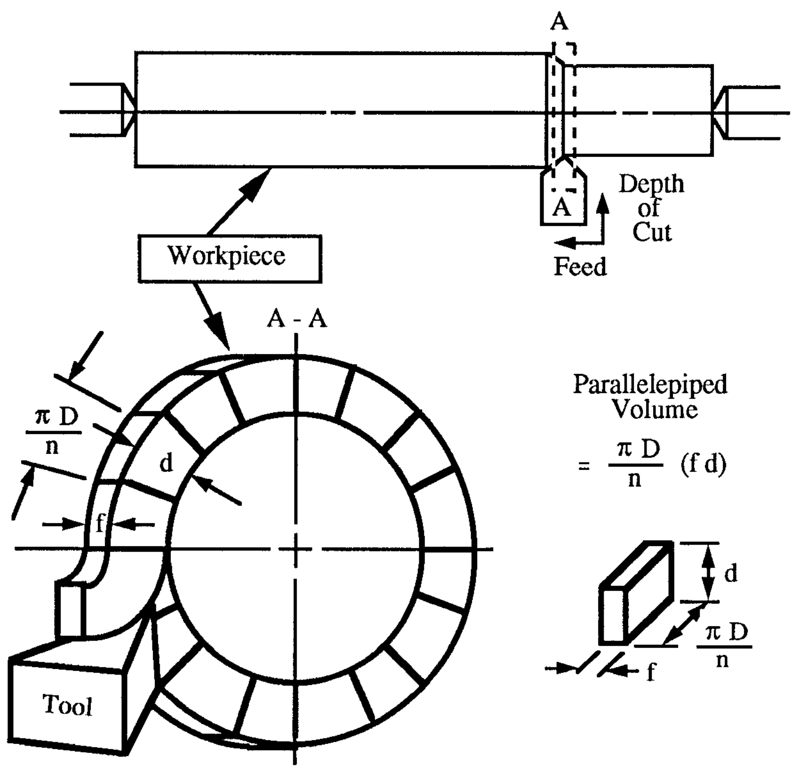



Fig. 5 Enlarged View of a Single-Point Turning Process

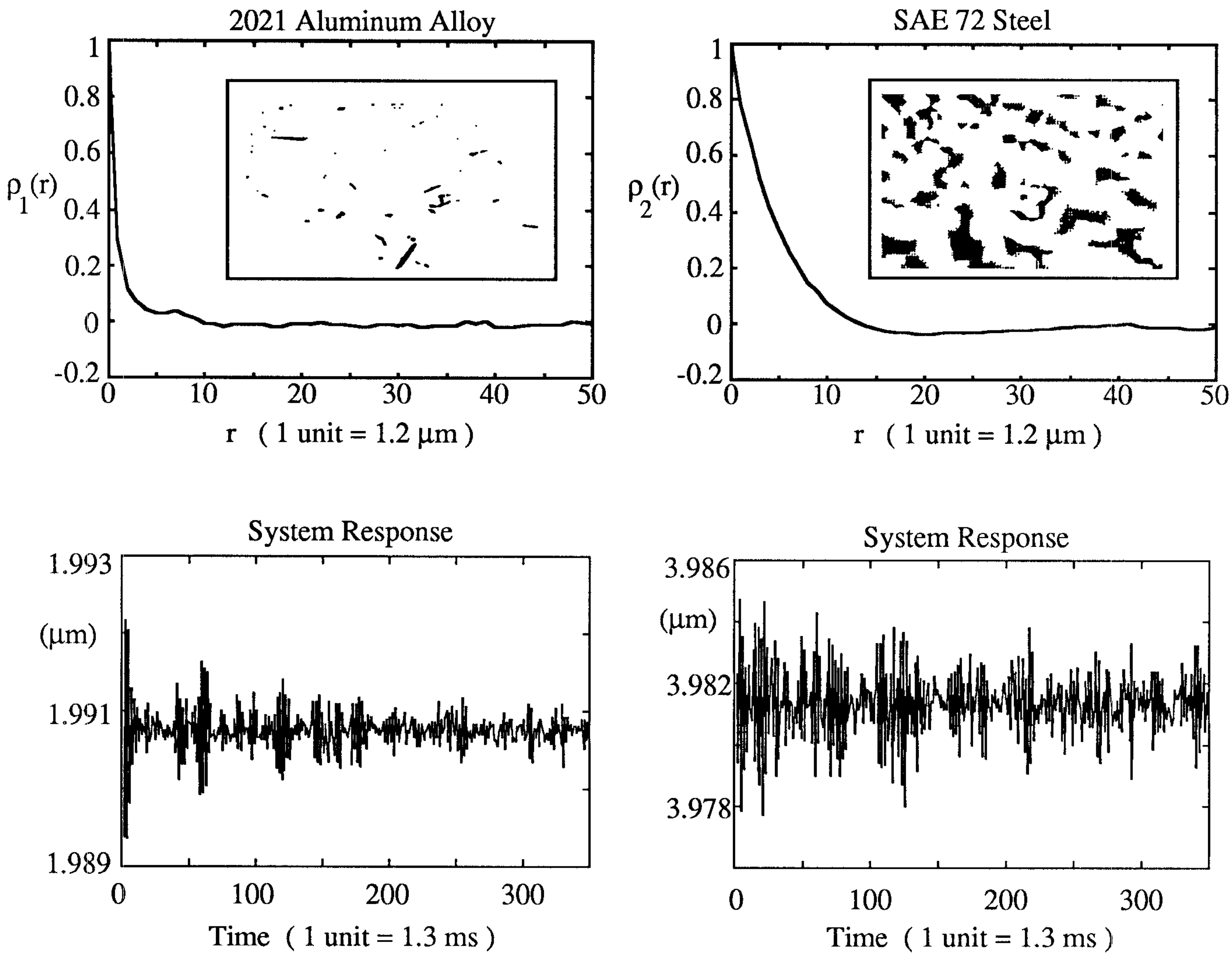



Fig. 6 Microstructural Analysis and Tool Vibratory Motion During Machining

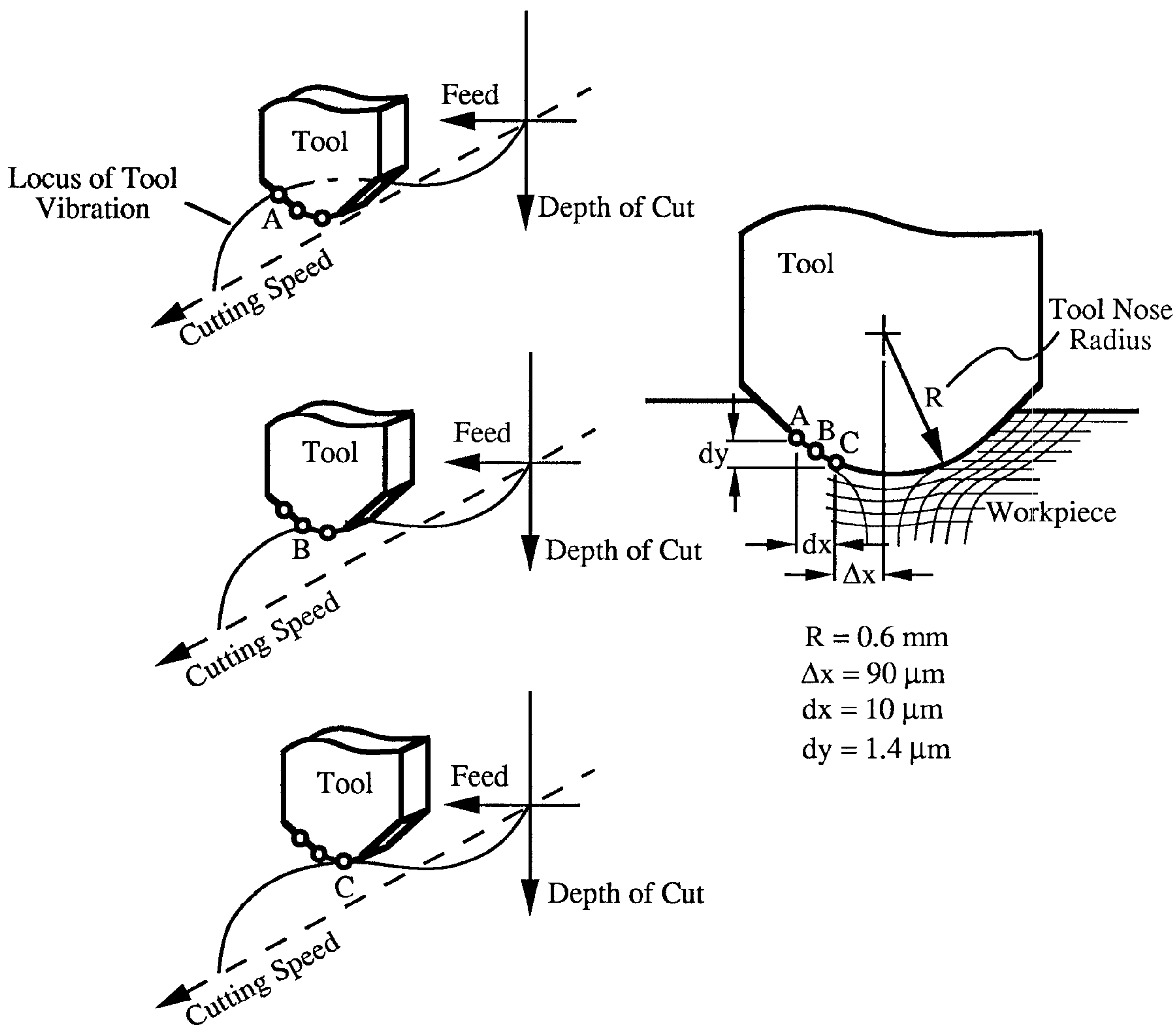



Fig. 7 Intuitive View of Surface Texture Generated during Machining

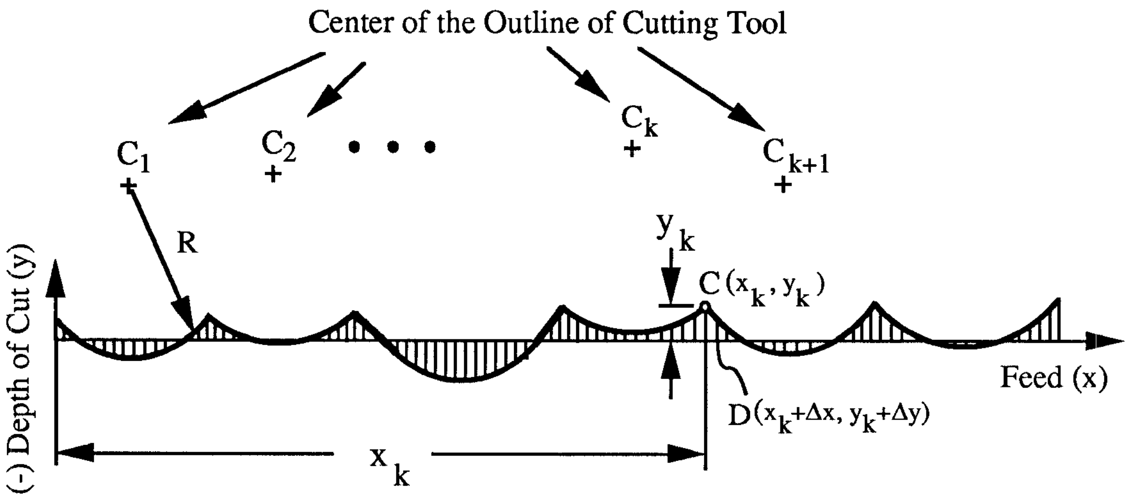



Fig. 8 Determination of Surface Profile along Feed Direction

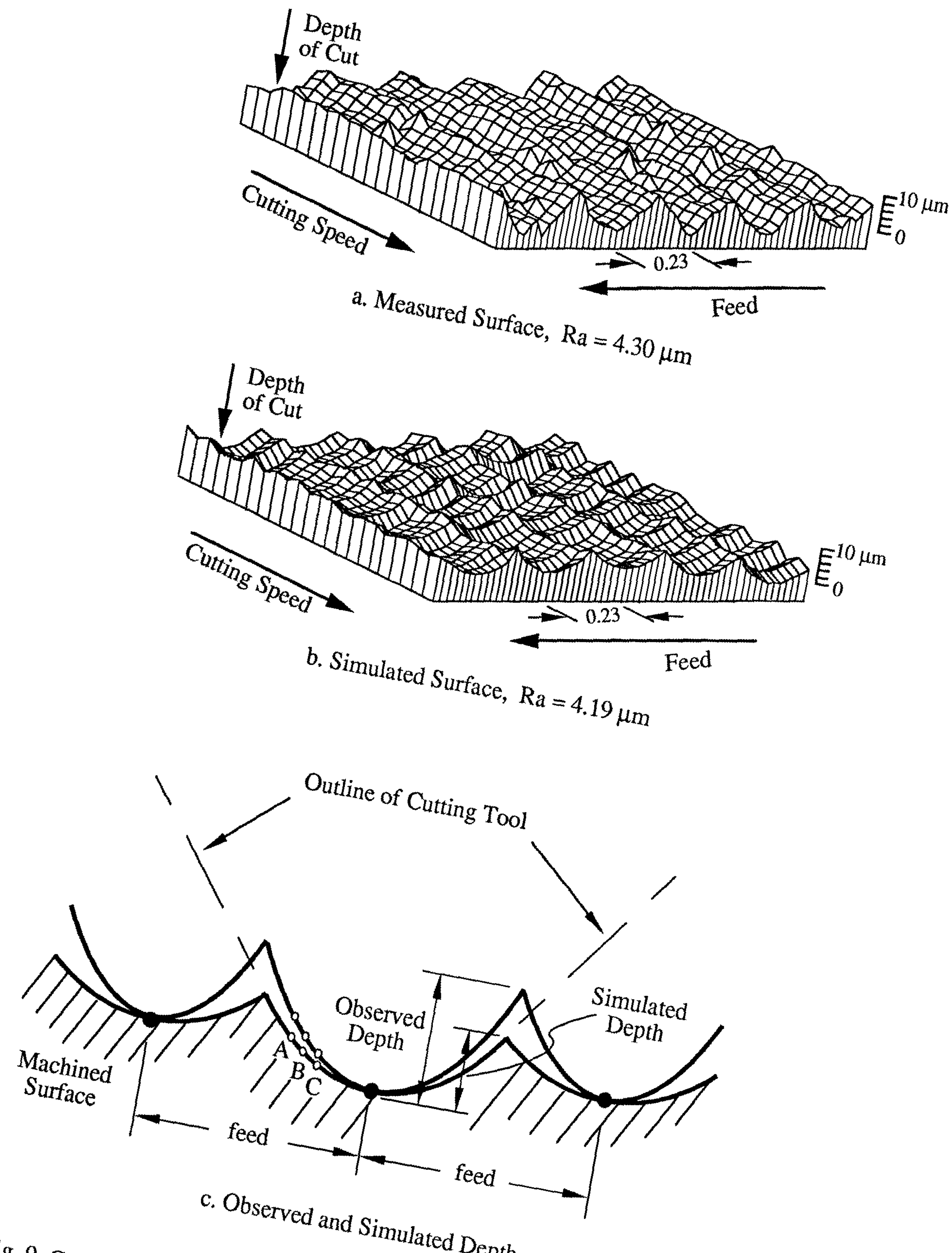



Fig. 9 Comparison between Measured and Simulated Surface Topographies (Feed: 0.23 mm/rev., Depth of Cut: 0.5 mm, Spindle Speed: 470 rpm, Tool Nose Radius: 0.6 mm).

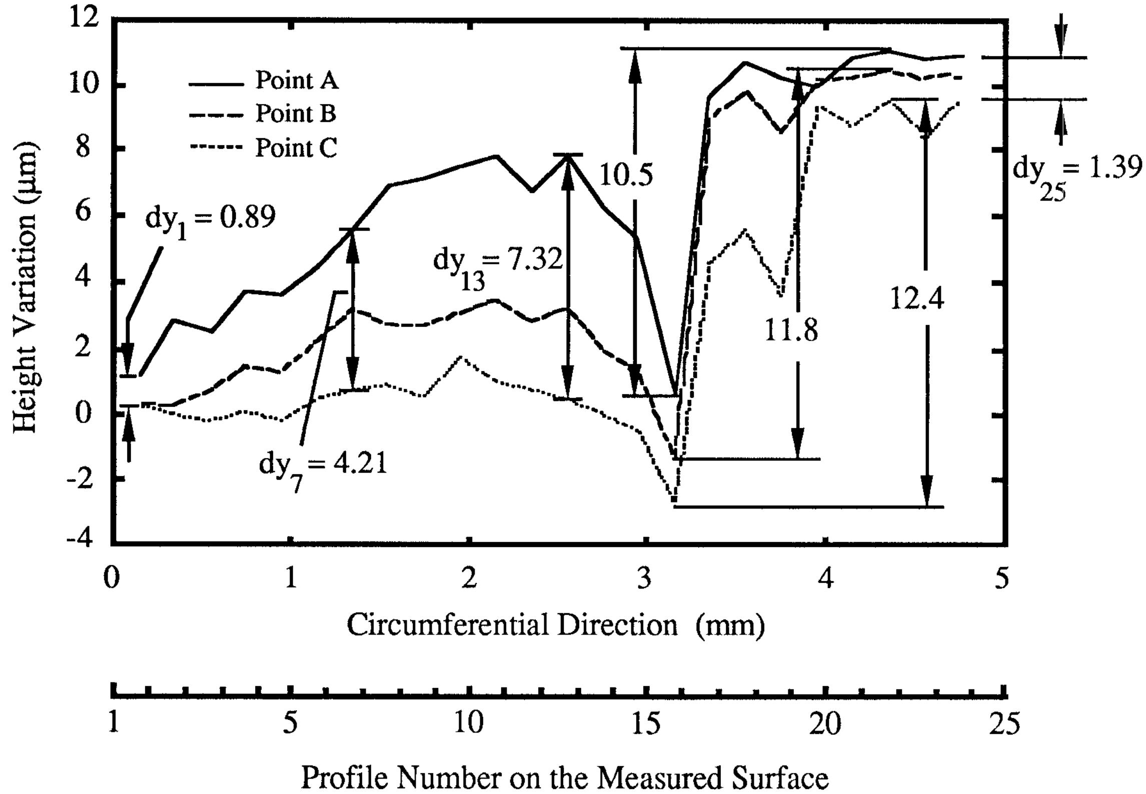



Fig. 10 Three Profiles Taken along the Circumferential Direction