An Experimental Study of Surface Roughness Assessment Using Image Processing

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Abstract

A surface roughness measurement technique, based on an area measurement method using a computer vision system, was investigated for applicability to in-process inspection of surface quality during a machining process. The vision system uses a monochrome CCD camera to provide a gray-scale image based on the pattern of light scattered from an area of the machined piece. This gray-scale image is sent to image manipulation software for analysis. For this investigation, an optical camera was used to photograph four aluminum samples with different roughnesses, and the resulting photographs were scanned into a computer using an 8-bit flat-bed scanner to produce the digital image used by the image manipulation software. Three parameters were derived from the images based on their gray-scale histograms, and these parameters were plotted against the corresponding average roughness (R_a) values determined using a stylus instrument. The resulting correlation curves were inspected to determine which optical parameter was most suitable for use in the system, based on relative accuracy and sensitivity of the parameters to changes in R_a.

1. Introduction

Producing the proper surface finish is an important part of any machining process. In order to ensure that machined parts have been manufactured with the desired surface roughness, a sample of the parts is typically examined after machining. The primary disadvantage of this post-machining inspection process is that it does not allow for corrections to be made during machining. Additionally, it becomes tedious to sort defective parts, since each part must be examined individually after being machined. The need for improved flexibility, productivity, and product quality in a modern manufacturing environment points to the need for high-speed in-process surface roughness measurement systems. In-process inspection of surface roughness during a machining process can provide a quality control check on the process, indicating if the surface finish of the machined part is within some predefined tolerance, without disrupting the production process. In-process inspection systems represent the key to successfully controlling product surface quality in a sensor-based manufacturing environment.

Regarding in-process inspection, traditional methods of surface roughness assessment have the disadvantage of requiring direct contact with the surface, as is the case with the common stylus-type devices. Such contact-based techniques are less than ideal for in-process inspection of surface roughness for several reasons:

- the measurement speed is limited due to the need for physical contact with the surface.
- non-continuous surfaces are extremely difficult to inspect, as the stylus tip must be navigated around any discontinuities in the surface.
- surface damage may occur due to wear between the stylus tip and the surface under inspection.
- the apparatus must be carefully isolated from vibrations, which can become difficult in a machining environment.

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- roughness values are determined using a limited number of single-line traces, which may not be representative the entire surface.
- the surface must be free of oil, dirt, and other contaminants -- in an actual machining environment, the surface must be cleaned, measured, and re-lubricated, which is expensive to implement as a high speed in-line process.

Recent research efforts in the manufacturing community have been focused on the development of improved, high precision machines, equipment and processes through advances in dimensional measurement techniques, sensors to monitor and control precision machines, and physical models of precision machining processes. The use of in-process surface roughness assessment represents one such area of interest. Several non-contact methods have been suggested as alternative surface roughness measurement techniques more suited for in-process inspection than traditional methods. For instance, laser-based profilometry systems and linear diode arrays can achieve faster measurement speeds (Jansson, 1984) than stylus methods by measuring the intensity of light reflected from the surface, but these methods suffer from an inability to characterize the entire surface topography. The ideal measurement system should combine the speed of laser-based systems, the accuracy of contact profiling techniques, and the ability to characterize a 2-dimensional region of the surface found in area-based topographic techniques such as capacitance or ultrasonic methods. This paper presents an experimental study of an area-based surface roughness assessment technique using image processing, which addresses each of these concerns.

2. Description of the Image-Processing Based Method

The roughness measurement system proposed here applies the light-scattering theory developed by Beckman and Spinoza (1963), which shows that the intensity field of light scattered from a rough surface can be described as a function of the surface topography. Using this insight, it should be possible to reconstruct an object's topographic (i.e. amplitude and wavelength) information, and thus surface roughness, by analyzing the pattern of light scattered from its surface. The photo-optical measurement method proposed here uses the apparatus shown in Figure 1. Here a sample is illuminated by a light source, and a CCD camera using a high magnification lens system provides a video signal which a frame grabber converts into an 8-bit digital image in real-time (30 frames per second). This image is then sent to a microcomputer for processing. The computer examines the light scattering pattern in the image, and calculates the roughness parameter of the surface from the image's gray-level histogram. The R_a value for the surface is then determined through the use of a correlation curve which uniquely relates a range of the roughness parameter to a range of R_a values. The resulting R_a value is either displayed on a video monitor for observation or used as feedback to the machining process.

The proposed apparatus avoids the pitfalls encountered by other methods of in-process roughness inspection. Since there is no physical contact with the surface, drawbacks such as low measurement speed, the need for navigation of non-continuous surfaces, and potential surface damage no longer present a problem. Vibration isolation is not difficult as the camera may be mounted relatively far from the surface under inspection. Since this technique is an area-based measurement method, it is capable of determining roughness values from a 2-dimensional region of the surface, and thus provides data more representative of the entire surface than single-line tracing methods.

Work on this topic has been done by Luk et al. (1989) in which a machine vision system was used to determine the surface roughness of several steel, copper, and brass samples. In this work, a camera and frame grabber were used to digitize an area of each sample, and the optical roughness parameter (R = std.dev./RMS) was calculated from the gray-scale images. A relationship was developed between known roughness values and the optical roughness parameter,

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and this relationship was used to test the repeatability of the optical method by comparing roughness values derived using the optical technique and a stylus device. It was found that the optical method produced more consistent readings than the stylus method when multiple measurements were made on a single sample, demonstrating that a computer vision system can be used to repeatably measure surface roughness. While the work by Luk et al. discusses the repeatability of this measurement technique, it fails to present an investigation into the accuracy of such a system. Inspection of the correlation curves presented in their paper reveals that there is quite a bit of variability in the roughness data collected using the computer vision system, resulting in large deviations between many data points and the curve fits through the data. An additional shortcoming of this work is that the lighting conditions used for the vision system limit the range of roughness values which the system can measure, due to the selection of a 5° 'grazing angle' between the light source and the surface of the sample.

The primary focus of this work has been in determining how to make the vision system capable of measuring surface roughness with sufficient accuracy. Ideally, the system precision would be in the same range as that of standard stylus measurement techniques. While the work by Luk et al. demonstrates the repeatability of vision-based roughness measurement systems, the potential accuracy of such systems remains to be seen. In order to make such a system viable for use in an automated industrial quality control system, the system must be capable of delivering high accuracy surface roughness measurements. We believe that the accuracy of the system is especially sensitive to the lighting conditions used to illuminate the surface, and that determining the ideal lighting conditions will result in improved system accuracy. Additionally, it must be determined which parameters of the digitized image can be best correlated to the surface roughness in order to provide acceptable accuracy and sensitivity to changes in R_a.

3. Experimental Study

The experimental study began with the preparation of samples of machined surfaces as illustrated in Figure 2. Four samples of aluminum, labeled A through D, were prepared under four different machining parameter settings to produce different surface roughnesses.

Each sample was photographed using a Nikon camera using high resolution black and white Kodak film. A high magnification lens system, capable of filling a standard 3 1/2" x 5" photograph with a 2.0cm x 1.4 cm image of the sample, was employed. Direct lighting was achieved using a 3.6W white light bulb to produce three sets of photographs of each sample. The lighting arrangement for each set is depicted in Figure 3. A set of photographs was also made under diffuse conditions, produced using a 150W light projected from behind the samples onto a white, granular mat designed to produce diffuse lighting conditions. Baseline conditions between different samples for a given lighting setup were maintained by simply swapping the samples without altering either the lighting or camera setup.

An additional photograph was made of a sheet of precision graph paper placed at the same focal point used for the sample photographs. This photograph was used to determine the scale of the samples. The photographs produced under diffuse lighting conditions are shown in Figure 4.

Each of the pictures resulting from the photo-optical apparatus were scanned into a Macintosh II microcomputer using an 8-bit (256 gray level) scanner, and the resulting gray-scale images were loaded into an image manipulation program for processing (*NIH Image** running on a Macintosh II microcomputer was used for this purpose). Using the library of functions available

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* NIH Image is a public domain image processing and analysis tool for the Macintosh II microcomputer written by Wayne Rasband at the National Institutes of Health

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under *NIH Image*, several macros were written to determine three image parameters: standard deviation (SD), arithmetical average deviation (AAD), and RMS values based on the brightness level histogram over a 12.5 mm^2 region of each image. These parameters are defined as follows:

$$SD = \sqrt{\frac{1}{n-1} \sum_{i=0}^{255} F_i (x_i - \bar{x})^2} \qquad RMS = \sqrt{\frac{1}{n} \sum_{i=0}^{255} F_i^2} \qquad AAD = \frac{1}{n} \sum_{i=1}^{n} |x_i - \bar{x}|$$

where n = # of pixels in the image, x_i = gray (brightness) level ($0 \leq i \leq 255$), and F_i = frequency count of pixels in the image at brightness level x_i. The parameter values calculated for each sample are listed in Table 1.

Table 1 - Optical and Stylus Parameters

Sample	(NIST) R_a	(Optically AAD	Derived RMS	Parameters) SD
A	2.9	18.109	134.909	12.872
B	0.9	85.578	96.362	45.808
C	4.9	33.037	119.993	28.453
D	4.0	51.892	107.737	33.639

With the image parameters determined, calibration data was required to produce the desired correlation curves. Facilities at the Ceramics Division of the National Institute of Standards and Technology (NIST) were used to measure the sample surface roughnesses. A Perthometer stylus device was used to calculate the average roughness index, R_a, for each sample averaged over multiple measurement trials. In addition to these stylus measurements, a series of 151 parallel traces were taken on the samples using a custom stylus-based apparatus developed at NIST. This device was designed for the purpose of producing a 3-dimensional reconstruction of the surface topography over a region of a surface. Figure 5 presents surface profiles traced from each of the four samples. The average R_a values are listed in Table 1.

4. Discussion of Results

4.1 Topographical Visualization

Numerical data obtained from both the stylus measurement and optical inspection methods are listed in Table 1. However, variations of both R_a and optical parameter values were observed across individual samples. These variations are due to the nature of the machining process employed to produce the samples. Therefore, the R_a data listed in Table 1 represents the mean level of R_a for the given sample. The variation of R_a across each sample can be observed qualitatively in the 3-dimensional reconstructions of the sample surfaces produced using *NIH Image*. These images, shown in Figure 6, were created by plotting the brightness level of the scanned image along the z-axis, with the sample's spatial coordinates in the x-y plane.

Examining these four topographic reconstructions, it is evident that the irregularities displayed in the topographic reconstruction from sample C, which has the largest R_a value, are much larger than those displayed in the topographic reconstructions from sample B, which has the smallest R_a value. This observation confirms that the optical inspection method has the capability to distinguish between different patterns of surface roughness. Figure 7 is the surface topography reconstructed from the surface roughness profilometer measurements. Similarity in appearance can be observed between the two methods of reconstruction. This also confirms the validity of applying the optical inspection method to surface roughness assessment. It should be noted that the profilometer-based topographic reconstruction required over 150 individual stylus traces, and

significant time investment, whereas the optical measurement method produced similar results for considerably less effort.

4.2 Logarithmic Regression Analysis

Figures 8a through 8c show graphs of each of the three optically-derived parameters (RMS, AAD, and SD) plotted against the known R_a values determined using the calibrated stylus measurement system at NIST. A logarithmic curve was found to achieve a good fit through the data, and these curves are shown in each of the graphs. For example, the logarithmic fit to the SD data results in the relationship $SD = 14.8(R_a^{0.659})$, with a good correlation coefficient ($R^2 = 0.852$. Since the exponential power of R_a represents the slope of the curve in log-space, a higher value for this exponent indicates increased sensitivity of the SD parameter to changes in R_a.

4.3 Sensitivity and Accuracy

Examination of the curve fits obtained by logarithmic regression in Figs. 8a through 8c shows that the curve fit to the RMS parameter data has the largest exponential value for R_a, indicating that this parameter is most sensitive to small variations in R_a. However, the logarithmic fit through the SD data provides the best correlation between the curve and data (an R^2 value of 0.852 for SD, as opposed to 0.666 for RMS and 0.637 for AAD), suggesting that this parameter may yield more accurate estimations of the average surface roughness than either of the other parameters. Since only four data points were used for this investigation, it is difficult to make broad claims regarding the accuracy and sensitivity of the optical parameters, but these preliminary values suggest that both the RMS and SD optical parameters are most useful in producing the desired correlation curves, while the AAD parameter is less than ideal.

4.4 Further Research

Clearly, more data needs to be collected in order to develop accurate correlation curves which are reasonably sensitive to variations in R_a. As well, the following topics deserve special attention for future research:

- *determination of ideal lighting conditions* - the intensity, incident angle, and proximity of the light source used to illuminate the surface were observed to have a strong effect on the optical parameters of the surface. The sensitivity of the optical parameters to, and the system accuracy under, different lighting conditions should be examined in order to determine which conditions provide the best results.
- *surface orientation independence* - ideally, the measured surface roughness should be independent of the orientation of the light source with respect to the surface under inspection. The variability of the optical roughness parameters with changes in lighting orientation needs to be investigated to establish whether the correlation curves are valid only for a given lighting orientation.
- *operable range of roughness values* - the surface roughnesses of the four samples in this investigation covered a wide range between 0.9μm and 4.9 μm. It is plausible that better results may have come from studying a smaller range of roughness values, or a range with a smaller upper limit.

5. Conclusions

This experimental study has been successful in examining the application of image processing techniques to surface roughness measurement, particularly for use as an in-process quality control tool. Overall, the experimental results of the surface roughness assessment method proposed here suggest that such a system is feasible. The system provides a fast and flexible method of performing surface roughness assessment which is well suited for use as an in-process inspection system. While this study was concerned with measuring the roughness of aluminum surfaces, the system can be adapted to other materials by developing a standard correlation curve for the material.

Acknowledgments

References

1. Beckmann P., Spizzichino, A., The Scattering of Electromagnetic Waves From Rough Surfaces, Oxford:Pergamon (1963).

2. Bolz R., Designing for Production ASME Handbook: Metals Engineering Design, 277-83 (1953).

3. Booker G., Scanning Electron Microscopy Modern Diffraction and Imaging Techniques, North Holland Publishing Company, 553-97 (1970).

4. Broadston J., Surface-Finish Requirements in Design ASME Handbook: Metals Engineering Design, 277-83 (1953).

5. Jansson D. G., Bourke J. M., High-speed surface roughness measurement, J. Eng. Ind. 106, 34-9 (1984).

6. Lyman T. (ed.), ASM Metals Handbook: Machining, American Society for Metals, 8th ed., 3, 169-93 (1967).

7. Luk F., Huynh V., North W., Measurement of Surface Roughness by a Machine Vision System, Journal of Physics E: Scientific Instruments 22, 977-80 (1989).

8. Thomas T., Rough Surfaces, Longman Group Ltd., Harlow, Essex UK (1982).

9. Vorburger T., Raja J., Surface Finish Metrology, NISTIR-4088, U.S. Dept. of Commerce (1990).
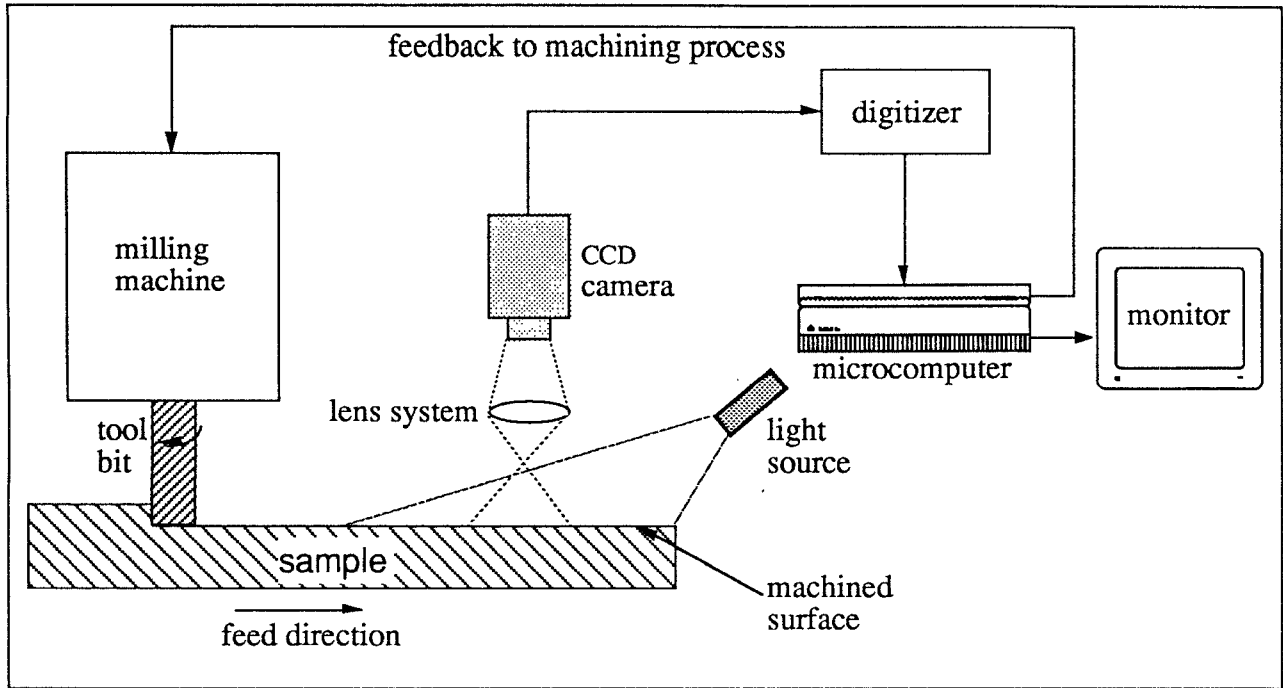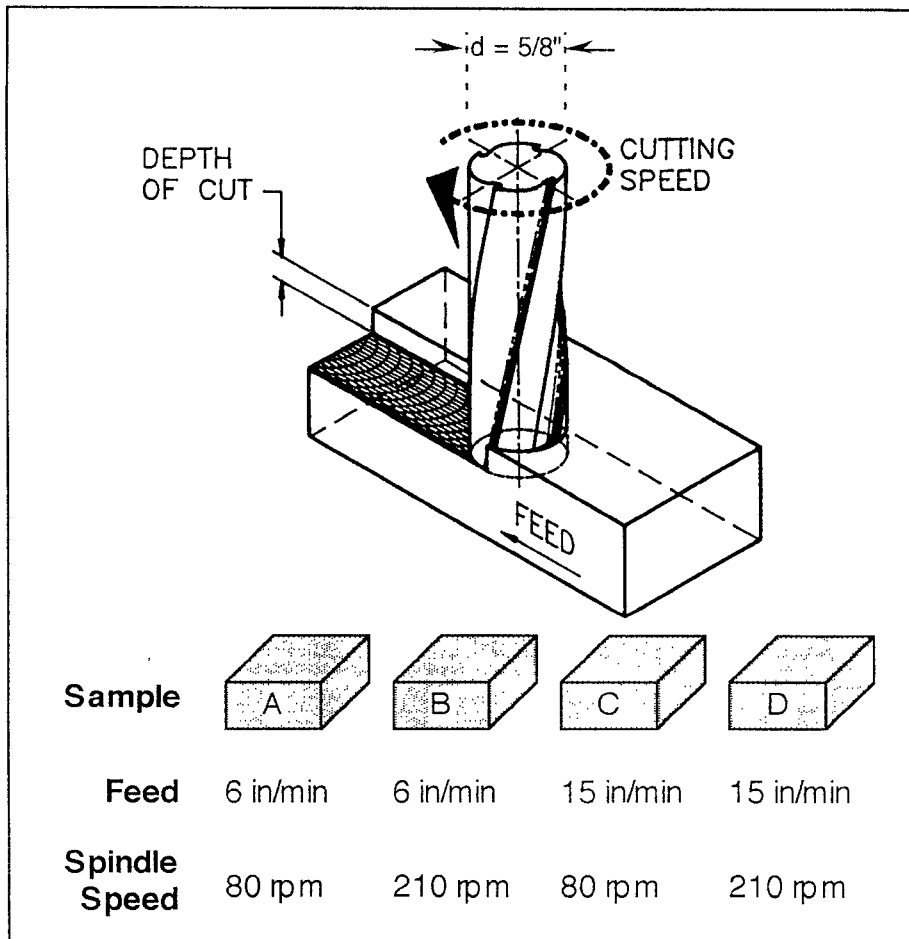
Figure 1 -- Ideal optical apparatus

Sample	A	B	C	D
Feed	6 in/min	6 in/min	15 in/min	15 in/min
Spindle Speed	80 rpm	210 rpm	80 rpm	210 rpm

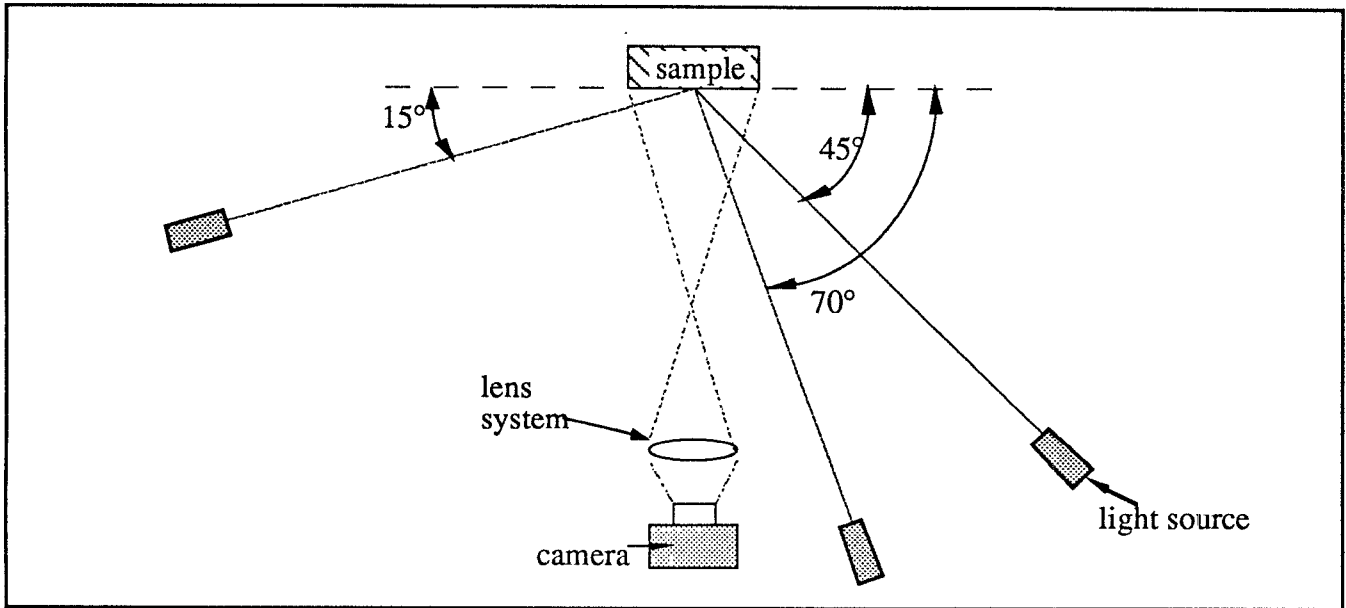**Figure 2** -- Machining parameter settings used to produce experimental samples
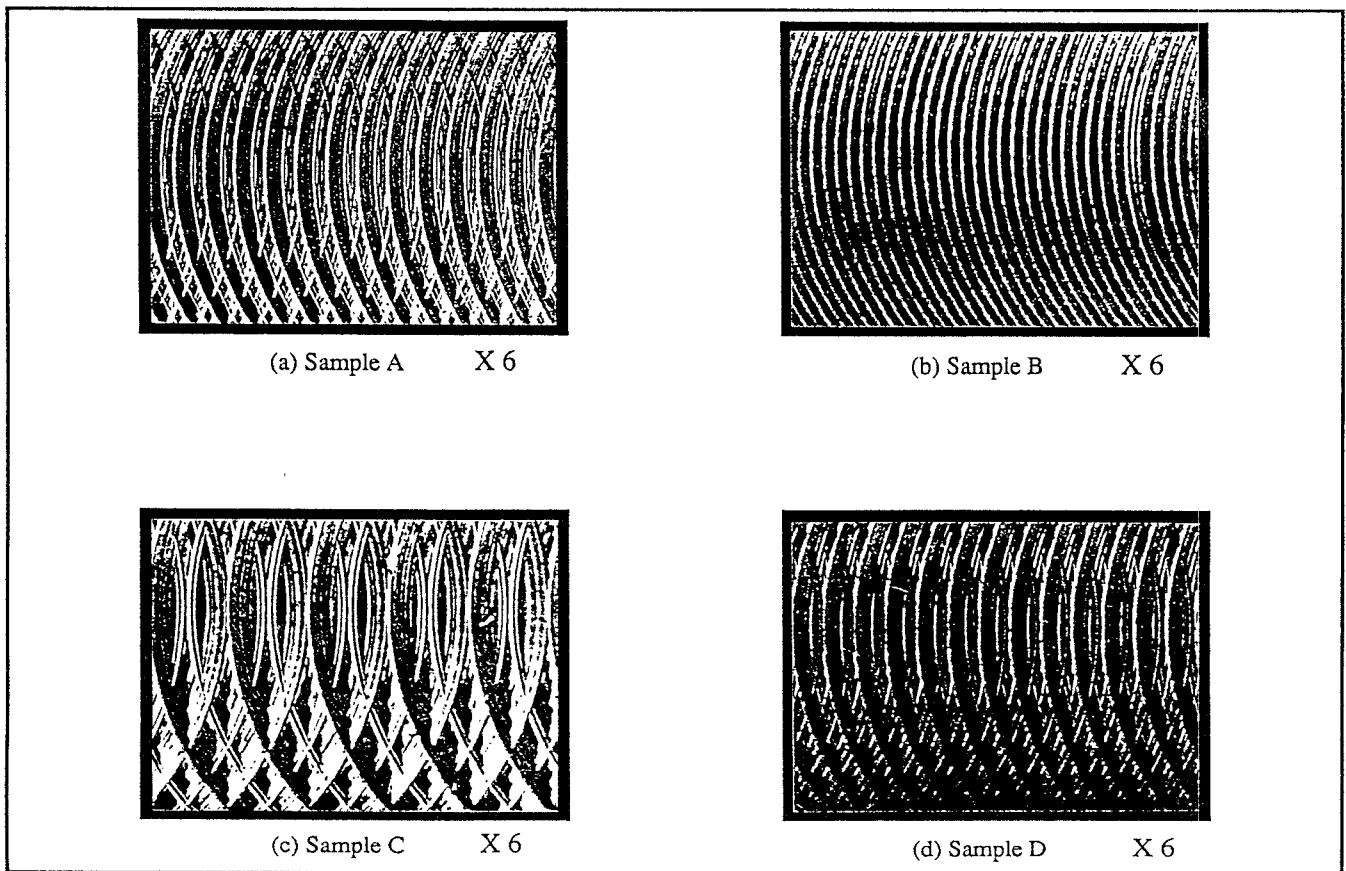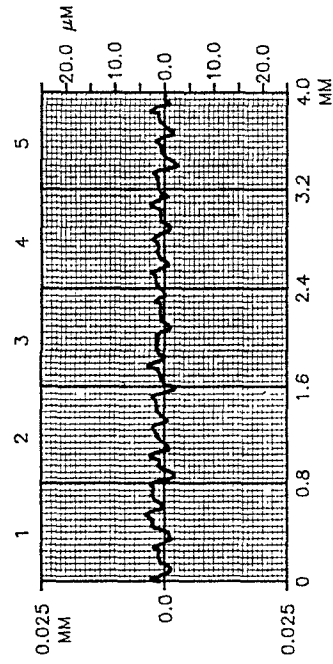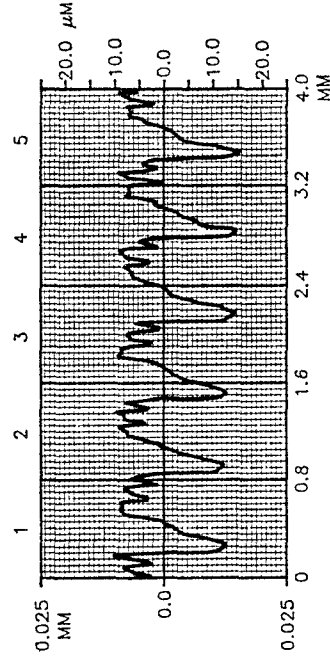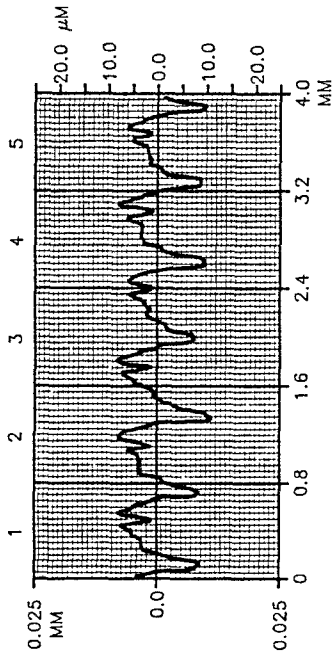
Figure 3 - Lighting system for photographs

(a) Sample A   X 6

(b) Sample B   X 6

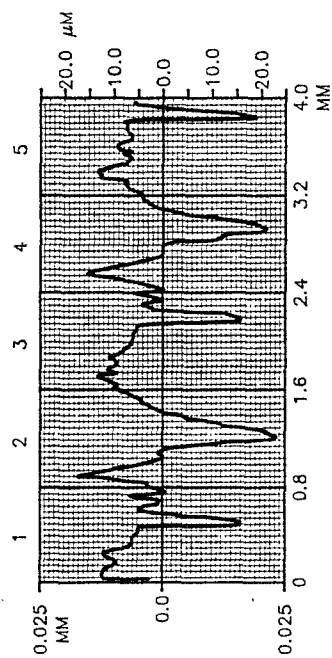(c) Sample C   X 6

(d) Sample D   X 6

Figure 4 - Photographs of aluminum samples

(a) Sample A, $\bar{R}_a = 2.9\ \mu m$

(b) Sample B, $\bar{R}_a = 0.9\ \mu m$

(c) Sample C, $\bar{R}_a = 4.9\ \mu m$

(d) Sample D, $\bar{R}_a = 4.0\ \mu m$
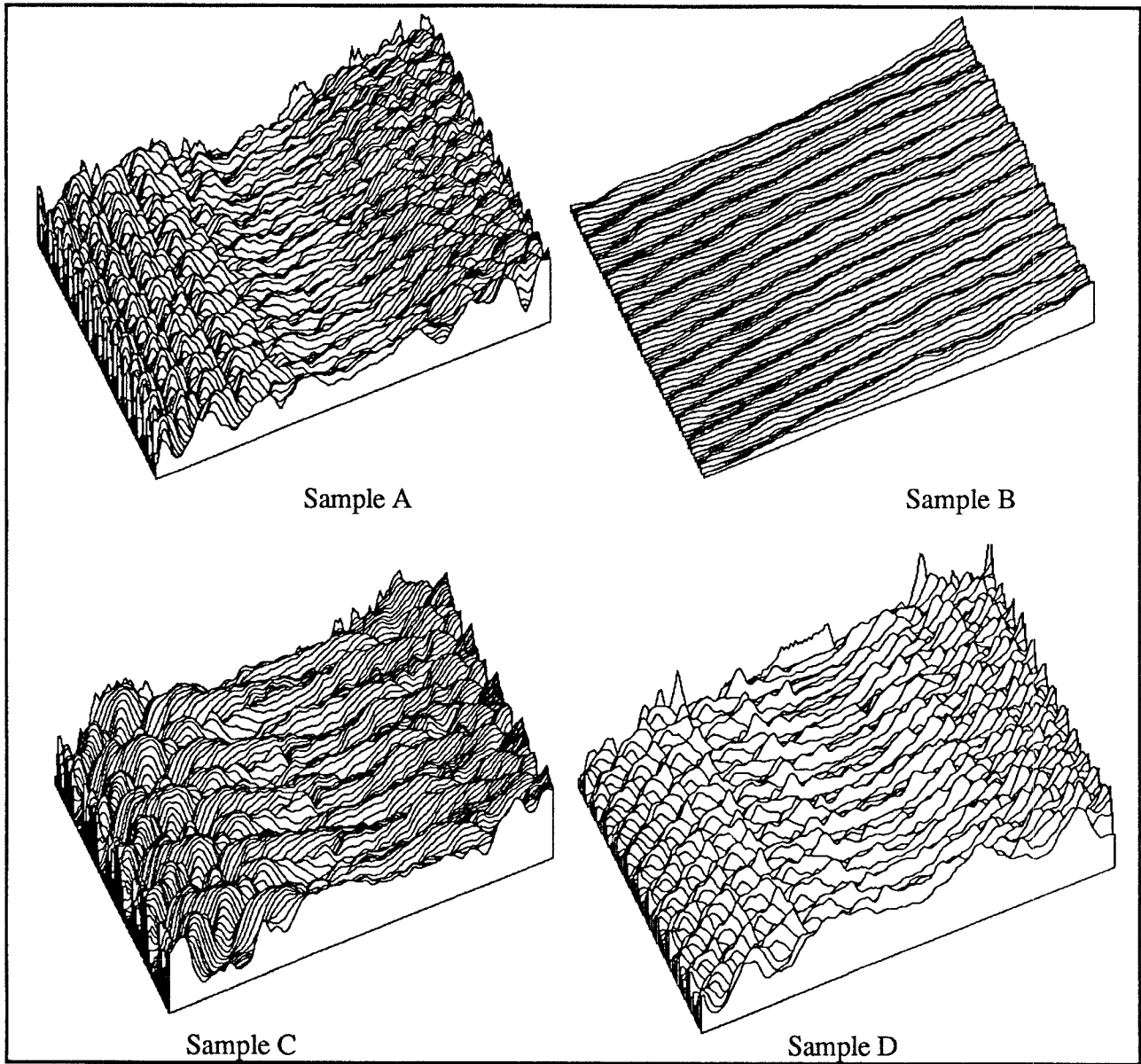
Figure 5 Surface Profiles Measured from the Four Samples

Sample A

Sample B

Sample C

Sample D
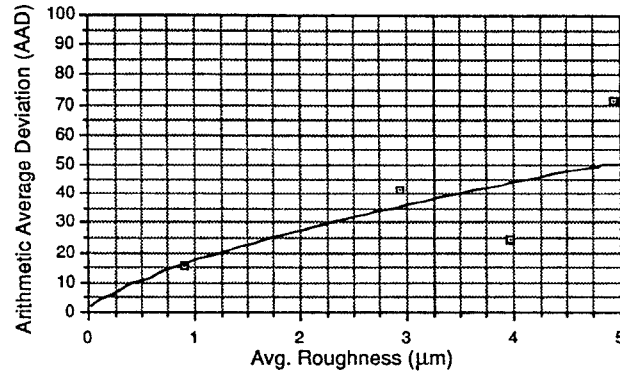
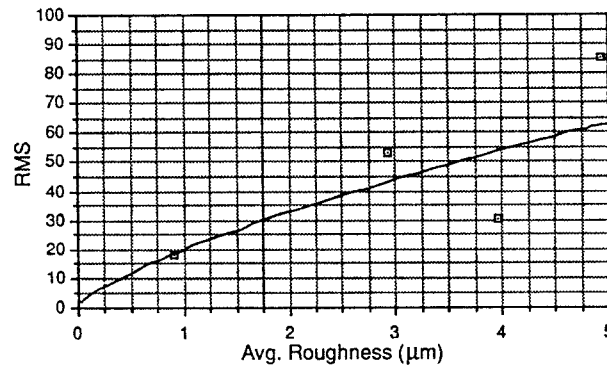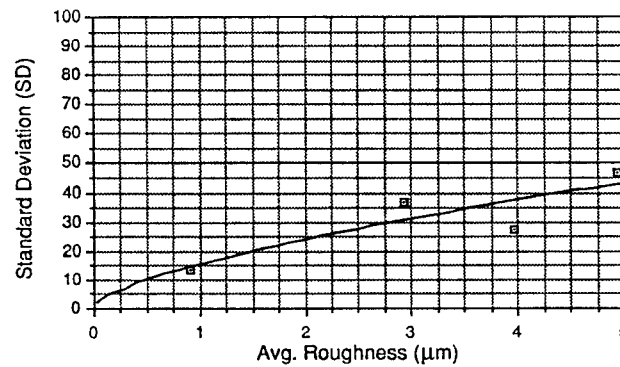**Figure 6** -- 3-dimensional reconstructions of surface topography using *NIH Image*
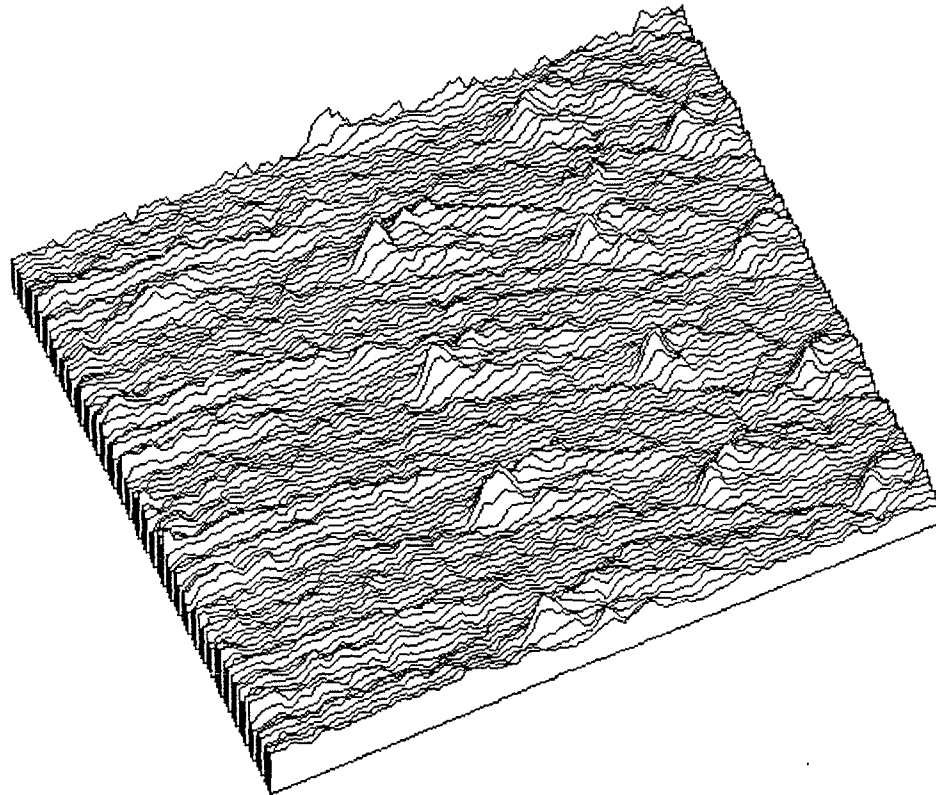
Figure 7 3- Dimensional Reconstruction of Surface Topography Using Stylus Instrument at NIST

(a) Arithmetic average deviation $AAD = 19.3(Ra^{0.693})$, and a correlation coefficient of $R^2 = 0.595$

(b) RMS, $RMS = 16.5(Ra^{0.732})$, and a correlation coefficient of $R^2 = 0.666$

(c) Standard deviation, $SD = 14.8(Ra^{0.659})$, and a correlation coefficient of $R^2 = 0.852$

Figure 8   Relationship between values of three parameters determined using optical inspection method and average roughness values determined using Perthometer stylus device at NIST.