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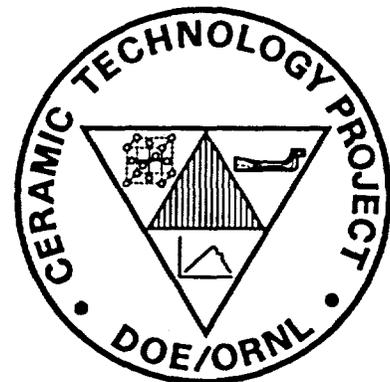
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A Comparison of Several Surface
Finish Measurement Methods as Applied
to Ground Ceramic and Metal Surfaces

Peter J. Blau, Rebecca L. Martin, and
Laura Riester

Ceramic Technology Project



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**A Comparison of Several Surface Finish Measurement Methods
as Applied to Ground Ceramic and Metal Surfaces**

) Peter J. Blau, Rebecca L. Martin, and Laura Riester

**Propulsion System Materials Program
Office of Transportation Technologies
Energy Efficiency and Renewable Energy
U.S. Department of Energy**

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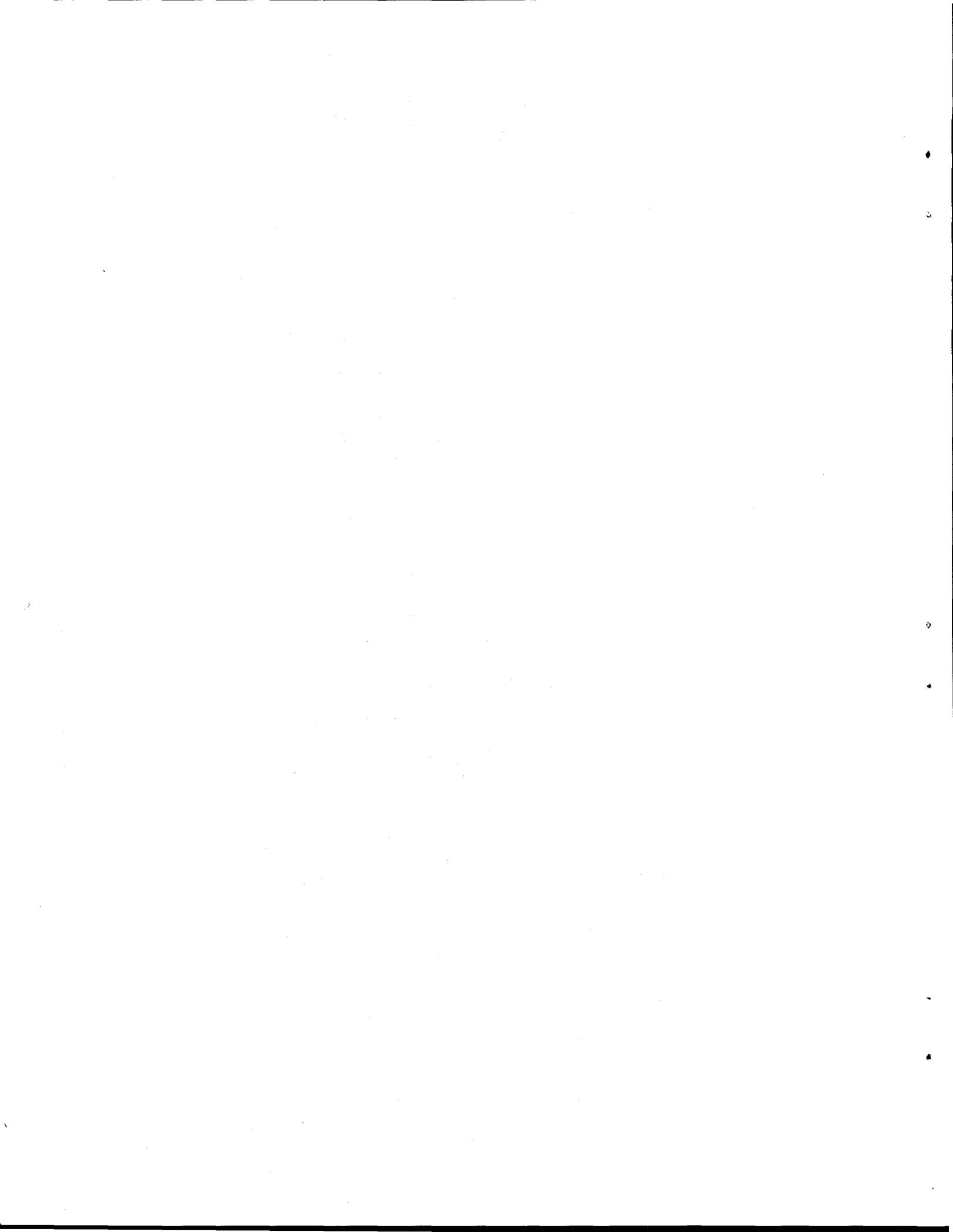
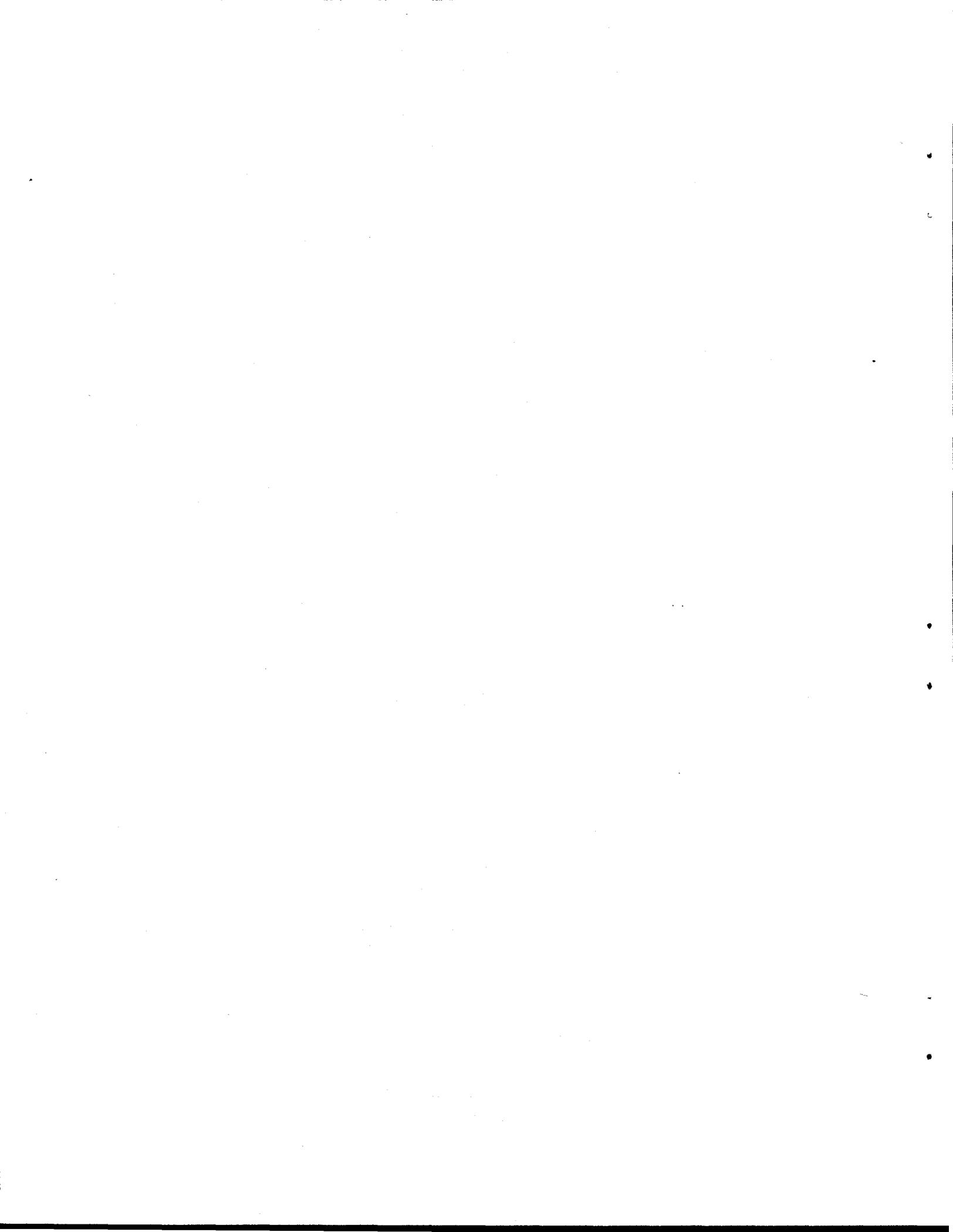


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EXECUTIVE SUMMARY

Surface finish is one of the most common measures of surface quality of ground ceramics and metal parts and a wide variety of methods and parameters have been developed to measure it. The purpose of this investigation was to compare the surface roughness parameters obtained on the same two specimens from three different types of measuring instruments: a traditional mechanical stylus system, a non-contact laser scanning system, and the atomic force microscope (two different AFM systems were compared). The same surface-ground silicon nitride and Inconel 625 alloy specimens were used for all measurements in this investigation. Significant differences in arithmetic average roughness, root-mean-square roughness, and peak-to-valley roughness were obtained when comparing data from the various topography measuring instruments. Non-contact methods agreed better with the others on the metal specimen than on the ceramic specimen. Reasons for these differences include the effective dimensions and geometry of the probe with respect to the surface topography, the reflectivity of the surface, and the type of filtering scheme selected by the operator. Results of this investigation emphasize the importance of rigorously specifying the manner of surface roughness measurement when either reporting roughness data or when requesting that roughness data be provided.

INTRODUCTION

Surface roughness, waviness, and lay are geometrical measures of surface quality and they are often used as criteria for the acceptance of finished parts. The characteristics of finished surfaces can determine the fit and function of the part in a larger machine or assembly. Therefore, considerable effort has been expended in quantifying surface roughness, waviness, and lay. Methods for their measurement range from the naked eye viewing and rubbing with a thumb to the use of ellipsometers and sophisticated atomic force microscopes. As various reviews have indicated, each method has inherent sources of error.^{1,2,3}

Not only are there numerous techniques for measuring surface roughness, but there are dozens of numerically-derived quantities used to characterize it. International standards have been developed to help reach consensus on the symbols and calculation of roughness parameters. To some extent the quantity or quantities selected for use with a given application are dependent on the nature of that application. For example, the presence of crevices in a surface can affect its lubricant retention capacity, and measures, like bearing area or kurtosis which relate to the depth and distribution of "valleys" in the surface profile, are selected to characterize such surfaces. In other cases, root-mean-square or arithmetic roughness is commonly used.

Recent years have witnessed the emergence of new methods of measuring surface roughness such as non-contact methods, involving laser-reflectance, and ultra-fine scale microscopy, like the atomic force microscope. Since the methods of obtaining the topographic data, on which the calculations of roughness parameters are based, differ between these new techniques, it is reasonable to question how closely the values of roughness parameters obtained on the same surface, but using different methods, will agree. It is the purpose of this experimental study to investigate that issue. The approach was to measure three roughness parameters of the same ground surface on three different types of instruments and to determine the degree to which they agree.

MEASUREMENT METHODS USED IN THIS INVESTIGATION

Three methods for measuring the surface roughness parameters were used, and one method, atomic force microscopy (AFM), was used on two different AFM instruments. We selected three measures of surface roughness and used four instruments to measure them. The roughness measures were arithmetic average roughness (R_a), root-mean-square roughness (R_q), and maximum peak-to-valley height (R_t). These are among the most commonly-used surface

roughness measures. They are defined as shown in Fig. 1. R_a is more commonly used than R_q . Due to the difference in computation, R_q tends to give more weight to larger values, thus R_a and R_q often differ. This effect is illustrated in Table 1. For establishing a baseline, we used a traditional mechanical contact stylus instrument which generates data based on a single linear traverse, and for comparison, we chose two other types of roughness instruments: a non-contact, laser scanning system and the atomic force microscope (AFM), both of which collect topographic data in a selected area.

The mechanical stylus tracing method was used as a baseline since it is perhaps the most widely used at the current time. The main elements of such a system are the stylus and pick-up, the traverse unit, the amplifier (whose gain establishes the magnification), a mode-selectable filter, and an output display or data storage device (Fig. 2). When the stylus moves along a surface containing a periodic array of grooves, such as might be generated during grinding, turning, or milling, the spacing of features generates a series of frequencies. The more closely-spaced the features, the higher-the frequency. To differentiate long-period waviness from the fine-scale roughness, electronic filters are used to establish a frequency cut-off. Dagnall recommends cut-offs of 0.25 - 2.5 mm for ground surfaces.⁴ For our investigation, we selected a cut-off of 0.25 mm. The number of cut-offs times the cut-off length equals the trace length of the stylus. In practice, a run-up length and over-travel allowance are added to the trace length so that data are obtained at constant velocity.

A Talysurf™ 10 (Rank Taylor Hobson Ltd., Leicester, England) with a 2.5 μm tip radius stylus was used in these experiments. A principal limitation of the technique arises from the finite size and shape of the stylus tip which prevents it from penetrating into deep crevices or detecting re-entrant features such as over-hanging material. The finite tip radius also limits its faithful replication of sharp edge features. The stylus displacement system has a position-sensitive, opto-electrical pick-up. The signal from the pick-up is processed by a desktop computer system with selectable filtration, cut-off length, number of cut-offs, and roughness parameters. Two modes of filtering were used in the collection of our data: unfiltered and ASME (ISO) filtration. Filters are typically used to suppress waviness or form constituents of the profile, to suppress the effects of vibrations, or to compensate for long-period trends in data arising from errors in aligning the specimen surface parallel to the trace direction. They may also be used to examine just the waviness aspects of the profile by suppressing the roughness components. The results of our studies show that it makes a difference in surface roughness parameters when the filter was used or not used.

The non-contact system used in this investigation was a Rodenstock RM 600 Topography Measuring Station. It measures roughness using an infrared laser whose beam is focused on the surface by an adjustable optical system (Fig. 3). This instrument allows acquisition of either 2-D single or 3-D multiple line scans from which each surface profile can be analyzed individually. The system software allows the user to select phase-correct filters, both cut-off (waviness) and stylus (to simulate a stylus instrument with given tip dimensions). The scanning conditions used on the stylus instrument were reproduced as much as possible on the non-contact instrument to permit a reasonable basis for comparing results. For example, the specimen was scanned in the same four areas in which mechanical traces were obtained and in the same scanning direction. A vertical height range of 30 μm and a scanning speed of 200 mm/min were selected. Each of the 50 scans acquired in a 1.25 mm² area contained 8000 data points.

A wave filter cutoff of 0.25 mm and stylus filters of both 1.0 and 2.0 μm were used. For averaging all scans in the sampling area, the assigned default filters of the system were selected (cut-off = 0.1786 mm and stylus 0.1 μm). A comparison of the data using default filter settings with those using 0.25 mm cutoff and 2.0 μm stylus showed no difference. Therefore the default filter values were not changed.

The AFM we used in this study (TopoMetrix, Santa Clara, California) utilizes a cantilever-type silicon nitride stylus that makes physical contact with the specimen. The stylus, having a < 50 nm tip radius, is mounted on a V-shaped, flexible cantilever which contacts the specimen with a pre-selected force. Its position is controlled by a tubular piezoelectric drive that travels in the Z-direction to maintain that force. The beam from a 2.5 watt diode laser is focused on the tip of the V-shaped cantilever, reflected off mirrors, and onto photocells that detect and track the movement of the beam. As the stylus moves across the surface at constant force, both the Z-travel and the cantilever movement are tracked. In the present work, a current of 1.12 nA was used to maintain the stylus force, the scan rate was 130.5 $\mu\text{m/s}$, and the resolution of the image was 400 x 400 lines. A diagram of that system is shown in Fig. 4.

SPECIMEN MATERIALS

A silicon nitride tile 25 x 25 x 6 mm (material: NCX 5102, Norton Company, Northboro, Mass.), was surface ground with a 400 grit diamond wheel with a depth of cut of 127.0 μm with a table speed of 0.127 m/s. A scanning electron micrograph of the as-ground surface is shown in Fig. 5. The surface, at high magnification, was not uniform, but instead consisted of some areas of smooth continuous grooves as well as localized areas of porosity, grinding-induced fracture, and grain fragmentation.

A 25 x 25 x 6.4 mm specimen of Inconel alloy 625 was prepared by dry hand grinding on 400 grit SiC papers. The surface of the metallic specimen exhibited a much higher brightness and reflectivity to visible light than the ceramic tile. A scanning electron micrograph of the surface is shown in Fig. 6. Long, continuous abrasion marks were observed. These exhibited the plastic features typical of abraded ductile metals and showed none of the fragmentation observed on the ceramic tile.

ROUGHNESS DATA

Mechanical profiling was performed at four locations comprising the corners of a 15 mm square on the top face of the ground silicon nitride tile. The other measurement methods were taken in the same vicinity, but avoiding the areas where the mechanical stylus may have caused surface damage on a microscale. Three filtered and three unfiltered passes were made at each location using 7 cutoffs 0.25 mm long. For each trace, 1610 data were recorded. An example of one trace is given in Fig. 7(a) and an enlargement of a portion of the trace showing individual data is given in Fig. 7(b).

Table 2(a) summarizes the Talysurf™ 10 roughness data from 24 traces (6 traces at each corner of the sampling area) on the ceramic tile, and Table 2(b) provides mechanical stylus data for the metal tile. Use of an ISO filter reduced the magnitude of the roughness parameters compared to the unfiltered condition, suggesting that there was a component of waviness in the raw profiles. The average roughnesses of the ceramic and metal specimens were relatively similar although the standard deviation in parameters for the metal specimen were somewhat greater.

Data from the infrared laser instrument is given in Table 3(a) and (b). Figure 8 illustrates the type of output the device provides. For the ceramic, the magnitude of roughness values are more than twice those in Table 2(a); however, the roughness values agree much better for the metal specimen. This suggests that the non-contact method we used in this work may not produce accurate results for less reflective surfaces such as medium-ground ceramics. One should recognize, however, that this conclusion may not apply to finely-ground or highly-polished ceramic surfaces.

Data from the two AFM instruments are given in Table 4 (a) and (b). Figure 9 shows a typical 90 x 90 μm area AFM image used for analysis on the first instrument. With a finer stylus tip, one would normally expect a larger value for the roughness since the tip could penetrate deeper crevices in the surface, but this expectation was not generally borne out by the data. It is possible that a slower scanning rate of the tip may have produced a greater difference between results obtained with two different tip sizes; however, this aspect of the methodology was not pursued here.

The AFM instrument can be configured to acquire roughness data for individual line scans as well as for area scans. We conducted an experiment on the metal specimen to compare area-averaged data with the data for single line scans placed perpendicular to the grinding marks at three locations on the same area. Results are compared in Table 5. Significant differences were found between R_a , R_q , and R_t data obtained from line scans and area scans over the same region of the specimen. Neither type of measurement was always either higher or lower than the other, so a consistent bias correction factor in using line scans instead of area scans could not be assigned.

Figure 10 summarizes the R_a and R_q results from four instruments on the ceramic (a) and metal (b) specimens. Figure 11 summarizes the data R_t as measured on both materials. Clearly, there is better agreement between techniques for the metallic specimen than for the ceramic specimen.

DISCUSSION

In the course of this work it has become increasingly clear that the effectiveness of one or another method for measuring surface roughness and the degree of agreement between one method and another is both specimen- and instrument-dependent. That is, the same instrumental technique may not work equally well on specimens with different types of surface features. These features may be categorized in terms of smoothness (i.e., the lack of sharp ridges or edges), regularity or periodicity of features, lack or presence of over-hanging (re-entrant) features, presence or absence of fragmented areas of disturbed material, and general uniformity of surface condition from place to place. Medium-ground ceramics, with their lower fracture toughness compared to metals, tend to exhibit more fragmented surface features and these features disturb the regular pattern of the grinding grooves. The amount of fragmentation can be reduced by adopting ductile grinding methods⁵ or high surface speeds.⁶ Metals, on the other hand, are generally more reflective and may be more amenable to measurement with non-contact instruments. Instrumentation-dependent factors include stylus or probe size, scanning speed, frequency response and sampling rate of the recording instrumentation, limitations due to feature slope or sharpness, sampling length or area, and the type of software used to filter and refine the raw data. With so many material-related and instrumental variables involved in the surface measurement process, it is little wonder that alternative measurements even on the same specimens may not necessarily agree.

The ability of the AFM to accurately represent a surface is limited by some of the same considerations as for the mechanical stylus instrument; namely, tip radius and filtering. As the scan is made, the stylus travels back and forth to produce a total of 400 lines. The piezo tube which adjusts the Z-motion acts like a cantilever, bending slightly back and forth with each pass. The filtered data in the AFM context is intended to compensate for that bending, and is therefore different from the waviness filtering that is done with the mechanical stylus.

One of the most unexpected findings of this work was that the stylus instrument produced higher values of peak-to-valley roughness than the AFM instruments in spite of the latter's much finer tips. This result flies in the face of logic that suggests that finer tips would detect the crevices in the surface that the mechanical stylus would slide over. Obviously, the explanation for this result is not straightforward. One possible explanation is that the stylus instrument "bounced" along the surface thus producing overshoots in the height data; however, we have no direct

evidence of stylus bouncing. Another is that the internal calibrations of one of the instruments were in error. To the best of our ability, and using reference grids, we could not detect a significant error in instrument calibration.

The fact that the non-contact laser produced relatively high values of the surface roughness parameters suggests that factors other than probe size must play a part in the measurements. These factors include leveling methods used in the software to establish the mid-line of the surface, the possible influence of reflectivity differences from place-to-place on the surface, and the filtering strategies present in the proprietary software with which the instruments are preprogrammed. It was not possible to examine the source code for the non-contact instrument, and therefore, not possible to establish how the raw data were treated to produce the output values of R_a , R_q , and R_t . Another possibility, in light of ceramic versus metal specimen data, is that the lower reflectivity of the ceramic affected the ability of the laser to detect the sharpest focus point for the reflected beam. If reflectivity problems with the ceramic were a source of error, than it may be possible to place a thin reflective coating on the ceramic surface, by physical or chemical vapor deposition methods, and remeasure the roughness. Of course, the assumption would have to be that the coating does not itself impart a new level of roughness to the surface. We decided not to try the coating approach for that reason and also because it is unlikely that such techniques would be used routinely in production.

The factors that are most likely to affect the agreement, or lack thereof, between the different measuring methods used here are as follows:

1. surface probe size or stylus tip radius
2. scanning speed of the probe
3. reflectivity of the specimen surface
4. uniformity or homogeneity of the specimen (place-to-place variations)
5. number of data taken to determine roughness parameters
6. filter method and selection of cut-offs
7. sharpness of surface features (slope severity, presence of re-entrant features, etc.)
8. the algorithms used within the measuring system to turn raw data into numerical values

In considering the present data, one is faced with the conclusion that the degree of agreement to be expected between alternative surface roughness measurement methods is a function of both the specimen characteristics and the methodology used. One cannot generalize that a particular method is always preferable to the others for determining surface roughness. Instead, the method should be selected to provide consistency (repeatability) and sufficient precision and accuracy for the given material and application.

If used for quality control, it is important that the same surface roughness method and set-up parameters be used for the entire inspection process to avoid problems in numerical agreement. Where surface finish is used as an acceptance criterion, it is doubly important that measurements be performed in the same way by the producer and the customer. Even if both sets of instruments check out equally well on standard grids or other model surface calibrating devices, they may not necessarily agree on the actual specimen being examined due to the aforementioned considerations.

CONCLUSIONS

Three techniques (mechanical tracing, atomic force microscopy (two tip sizes), and laser profiling) were used to measure R_a , R_q , and R_t on the same two ceramic and metallic specimens. Within the limitations of each method, an attempt was made to use similar sampling areas and dimensions. In general, the laser-based, non-contact method gave higher values; especially for the ceramic specimen. Numerical values for roughness parameters among the three techniques obtained agreed somewhat better on the metallic specimen than on the ceramic specimen. This may

have been caused by the effects of lower reflectivity and more fragmentation of features on the ceramic coupon than on the metal coupon.

Even though contact and non-contact surface roughness instruments may give accurate numerical results on standard test specimens, the peculiarities in the micro-geometry of different types of engineering materials may lead to disparate results when measured with surface roughness systems which operate under different principles of height sensing and data reduction.

ACKNOWLEDGEMENTS

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Table 1.

Comparison of R_a and R_q for Two Hypothetical Sets of Data

	Set 1	Set 2
"Data"	2, 2, 4, 4, 6, 6	1, 1, 4, 4, 7, 7
Number of data	6	6
R_a	4	4
R_q	4.32	4.72

Table 2(a).

Summary of Mechanical Stylus Roughness Data for the Ceramic Specimen

(12 stylus traces for each reported value)

	Average	Std. Dev.
R_a filtered	0.305	0.021
R_a unfiltered	0.340	0.028
R_q filtered	0.395	0.021
R_q unfiltered	0.455	0.007
R_t filtered	2.80	0.14
R_t unfiltered	3.20	0.42

Table 2(b).

Summary of Mechanical Stylus Roughness Data for the Metal Specimen

(3 stylus traces for each reported value)

	Average	Standard Deviation
R_a filtered	0.39	0.131
R_a unfiltered	0.72	0.191
R_q filtered	0.52	0.175
R_q unfiltered	0.97	0.202
R_t filtered	2.90	0.755
R_t unfiltered	4.40	0.781

Table 3(a).

Summary of Non-Contact Laser Roughness Data for the Ceramic Specimen

(12 area scans averaged for each reported value, 0.25 cut-off filter, 4 μm stylus filter, 30 μm range, 20 mm/s speed, 8000 data per scan)

	Average	Standard Deviation
R_a	0.858	0.063
R_q	1.111	0.090
R_t	7.530	0.933

Table 3(b).

Summary of Non-Contact Laser Roughness Data for the Metal Specimen

(12 area scans averaged for each reported value, 0.25 cut-off filter, 4 μm stylus filter, 30 μm range, 20 mm/s speed, 8000 data per scan)

	Average	Standard Deviation
R_a	0.361	0.057
R_q	0.476	0.079
R_t	3.713	0.702

Table 4(a).

**Atomic Force Microscope
Data on the Ceramic Specimen**

Instrument	Scan Area (μm)	Conditions	R_a (μm)	R_q (μm)	R_t (μm)
AFM #1	90 x 90	unfiltered	0.171	0.284	0.994
AFM #2	150 x 150	normal tip	0.234	---	0.962
AFM #2	150 x 150	"Supertip"	0.323	0.396	1.114

Table 4(b).

**Atomic Force Microscope
Data on the Metal Specimen**

Instrument	Scan Area (μm)	Conditions	R_a (μm)	R_q (μm)	R_t (μm)
AFM #1	100 x 100	normal tip	0.176	0.217	1.789
AFM #2	100 x 100	normal tip	0.492	0.561	2.29
AFM #2	100 x 100	"Supertip"	0.187	0.233	1.59

Table 5.

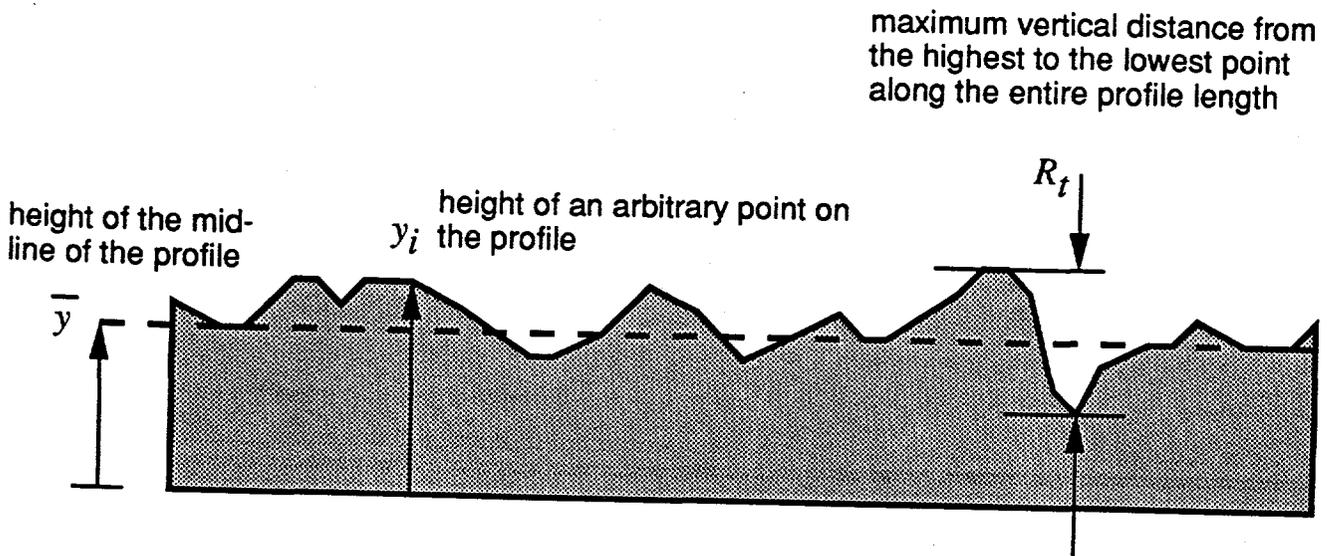
**Comparison of Line-by-Line Roughness Data with
Area-Based Roughness Data on the Metal Specimen**

(average of three line traces across the same 100 x 100 μm area used for the area scan)

Parameter	3 line Average (μm)	Area Scan (μm)
normal tip:		
R_a	0.501	0.492
R_q	0.840	0.561
R_t	1.846	2.290
"Supertip":		
R_a	0.179	0.187
R_q	0.471	0.233
R_t	1.150	1.590

Figure Captions

- Figure 1. Definitions of arithmetic roughness (R_a), root-mean-square roughness (R_q), and peak-to-valley roughness (R_t).
- Figure 2. Diagram of the mechanical stylus system used to acquire roughness data on the two specimens. (adapted from Ref. [1])
- Figure 3. Diagram of the non-contact laser system used to acquire roughness data on the two specimens.
- Figure 4. Diagram of the atomic force microscope system used to acquire roughness data on the two specimens.
- Figure 5. Scanning electron micrograph of the ground NCX-5102 ceramic tile. Orig. mag. 2000X
- Figure 6. Scanning electron micrograph of the abraded Inconel 625 specimen. Orig. mag. 2000 X.
- Figure 7. Illustration of a mechanical stylus trace of the ceramic surface. (a) normal profile, (b) enlargement of a portion of the trace to show the individual data more clearly.
- Figure 8. Illustration of the output the non-contact device.
- Figure 9. Typical 90 x 90 μm area AFM image used for analysis on the first instrument.
- Figure 10. R_a and R_q results from four instruments on the ceramic (a) and metal (b) specimens.
- Figure 11. R_t data for both materials.



$$R_a = \frac{1}{n} \sum_{i=1}^n |y_i - \bar{y}|$$

where n = the number of data taken along the sampling length

$$R_q = \sqrt{\frac{1}{n} \sum (y_i - \bar{y})^2}$$

Figure 1. Definitions of arithmetic roughness (R_a), root-mean-square roughness (R_q), and peak-to-valley roughness (R_t).

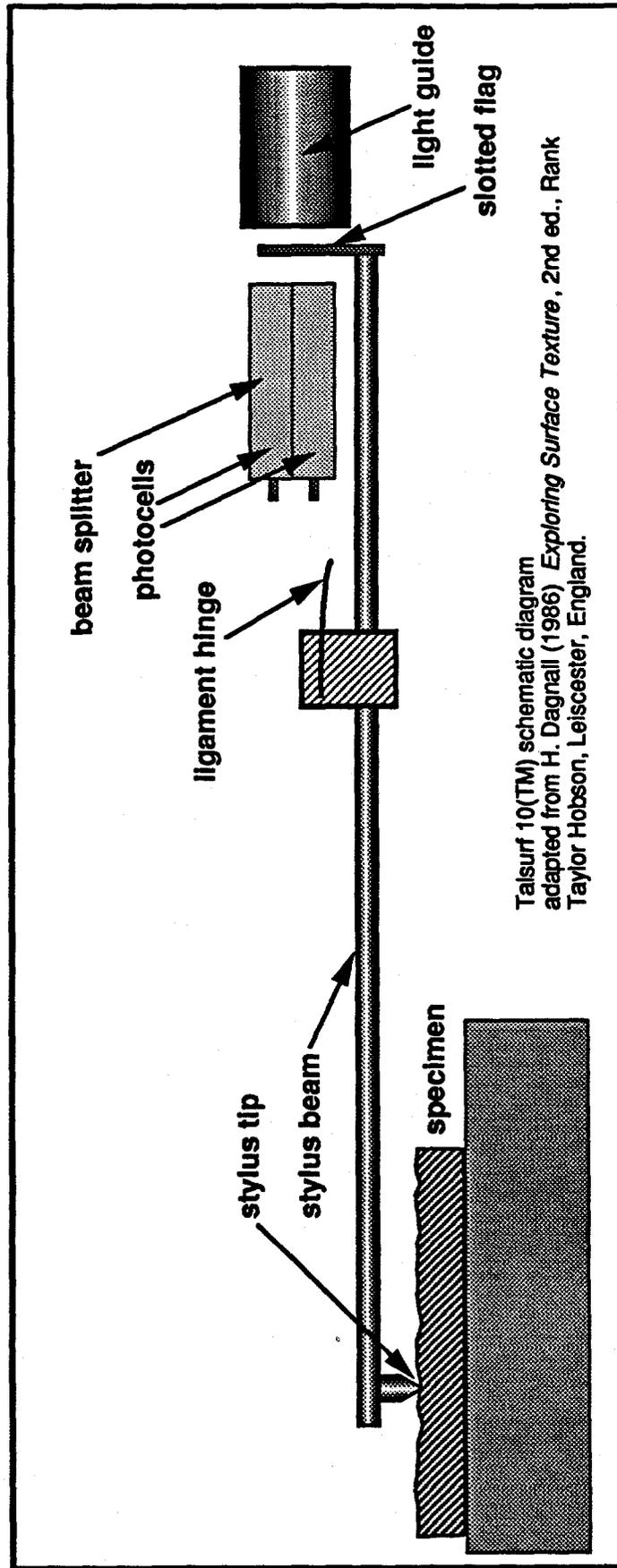


Figure 2. Diagram of the mechanical stylus system used to acquire roughness data on the two specimens. (adapted from Ref. [1])

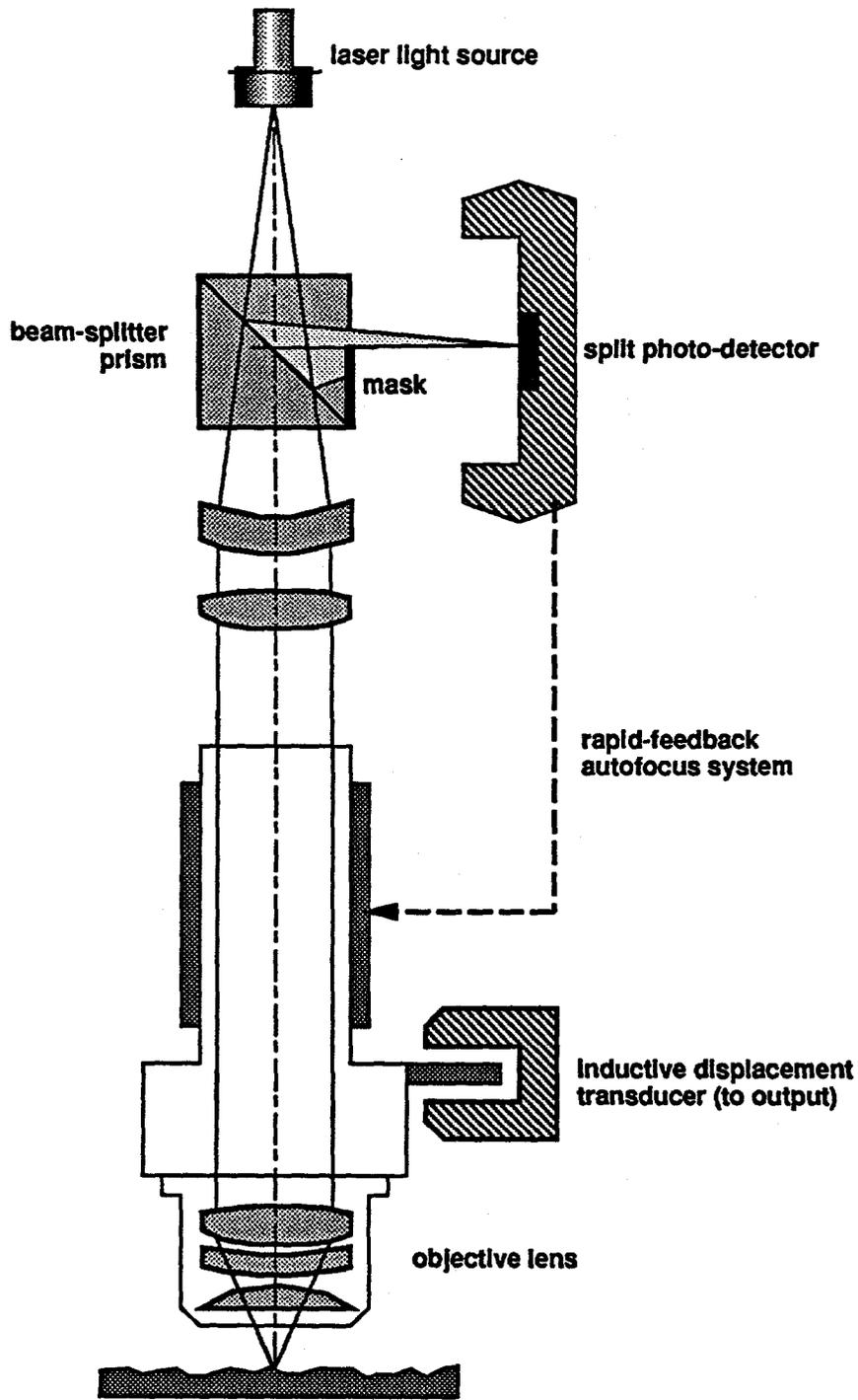


Figure 3. Diagram of the non-contact laser system used to acquire roughness data on the two specimens.

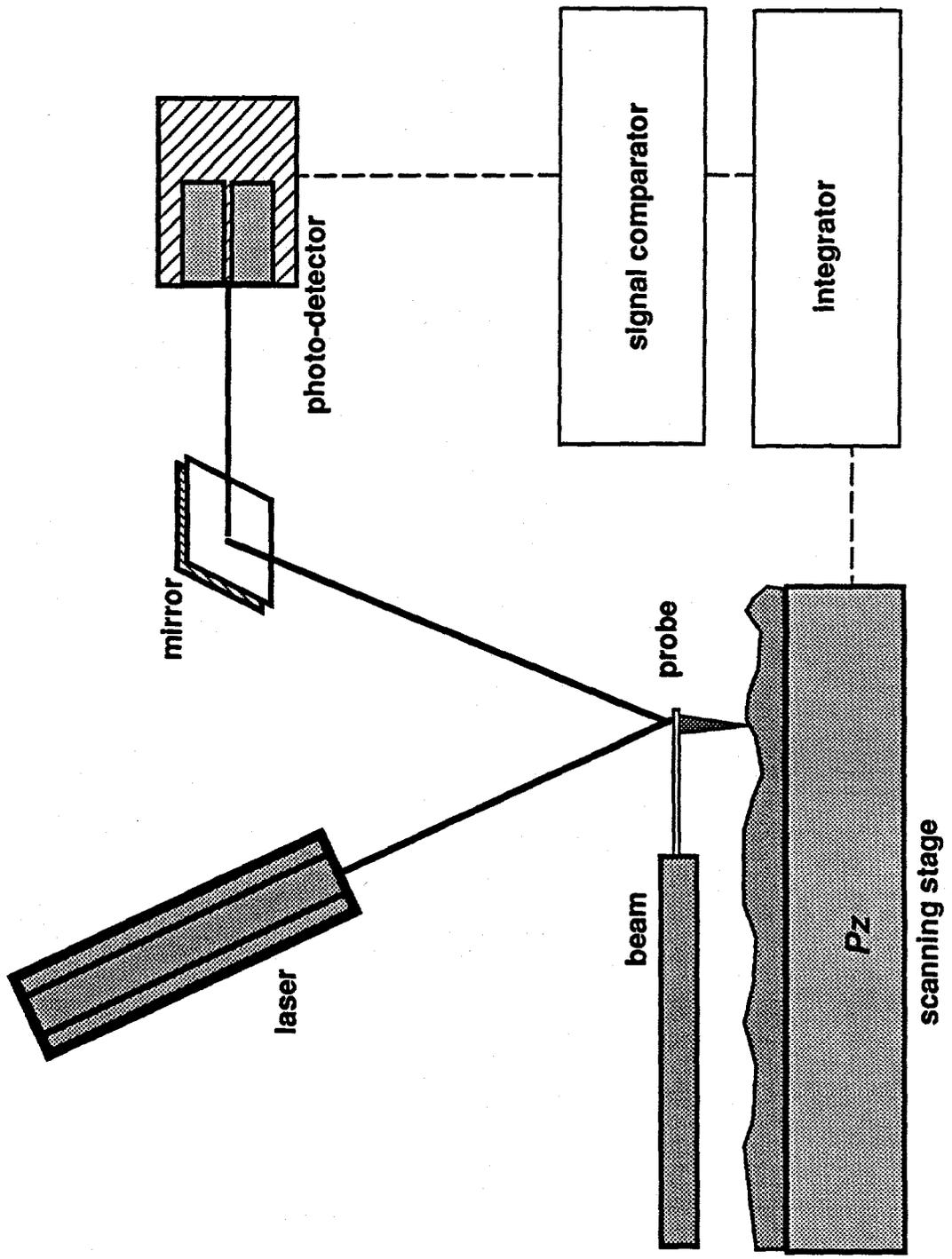
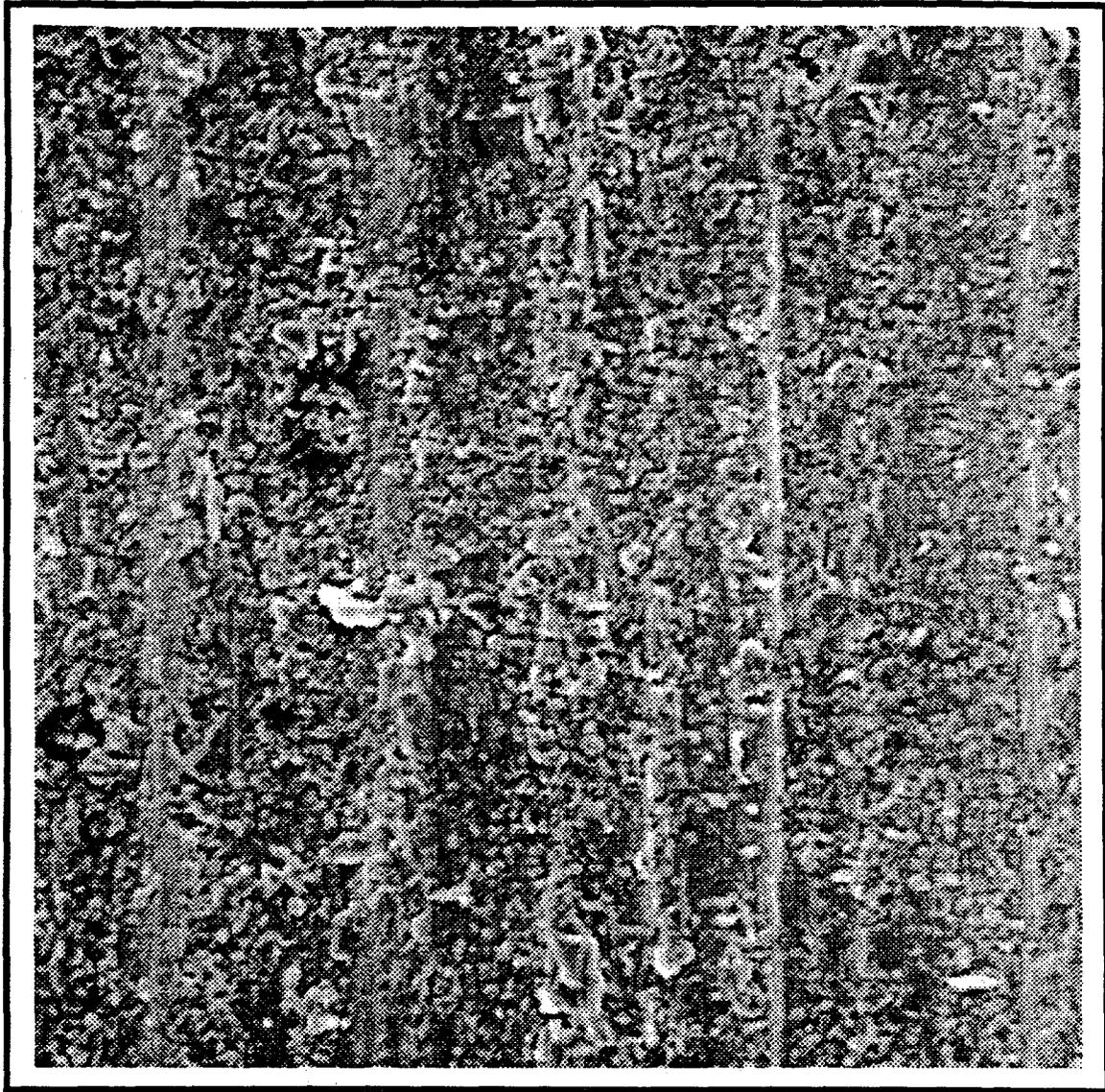


Figure 4. Diagram of the atomic force microscope system used to acquire roughness data on the two specimens.



5.0 μm

Figure 5. Scanning electron micrograph of the ground NCX-5102 ceramic tile. Orig. mag. 2000X



5.0 μm

Figure 6. Scanning electron micrograph of the abraded Inconel 625 specimen. Orig. mag. 2000 X.

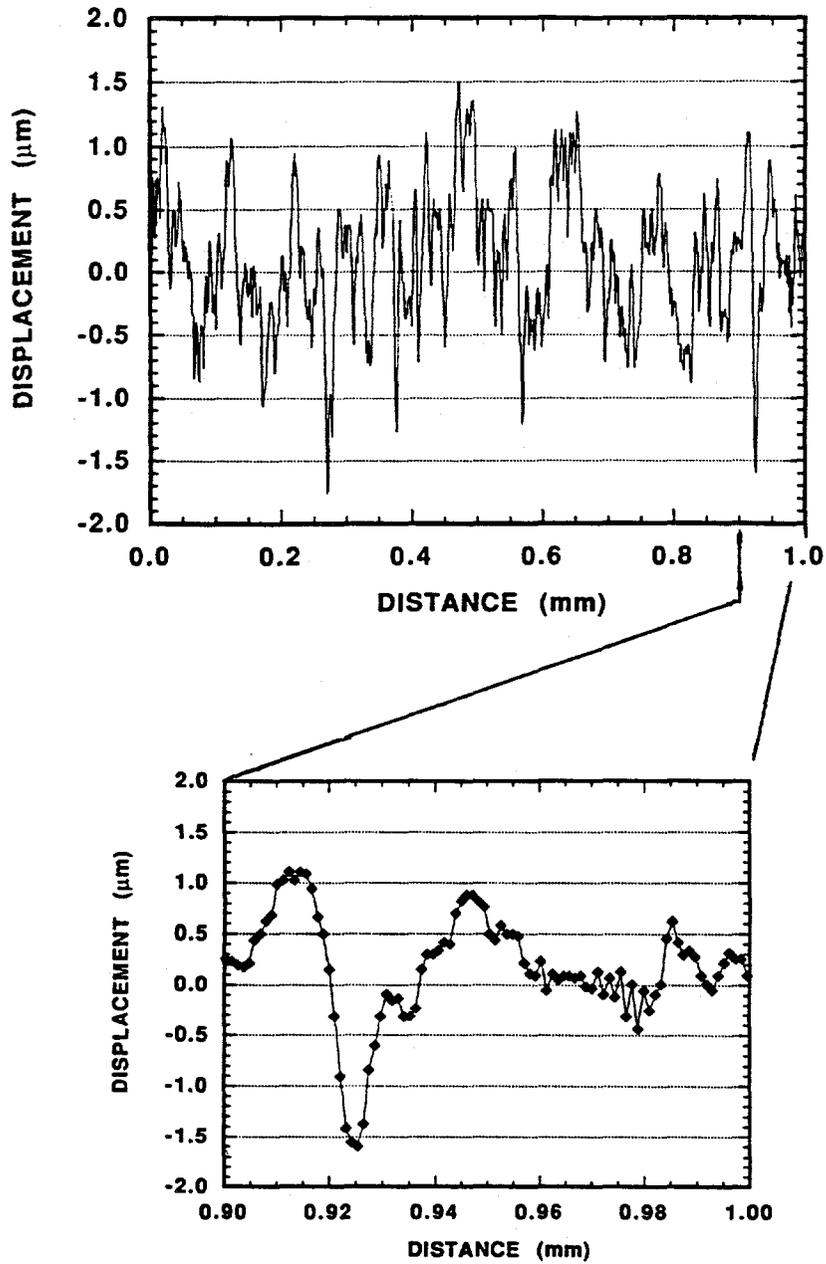


Figure 7. Illustration of a mechanical stylus trace of the ceramic surface. (a) normal profile, (b) enlargement of a portion of the trace to show the individual data more clearly.

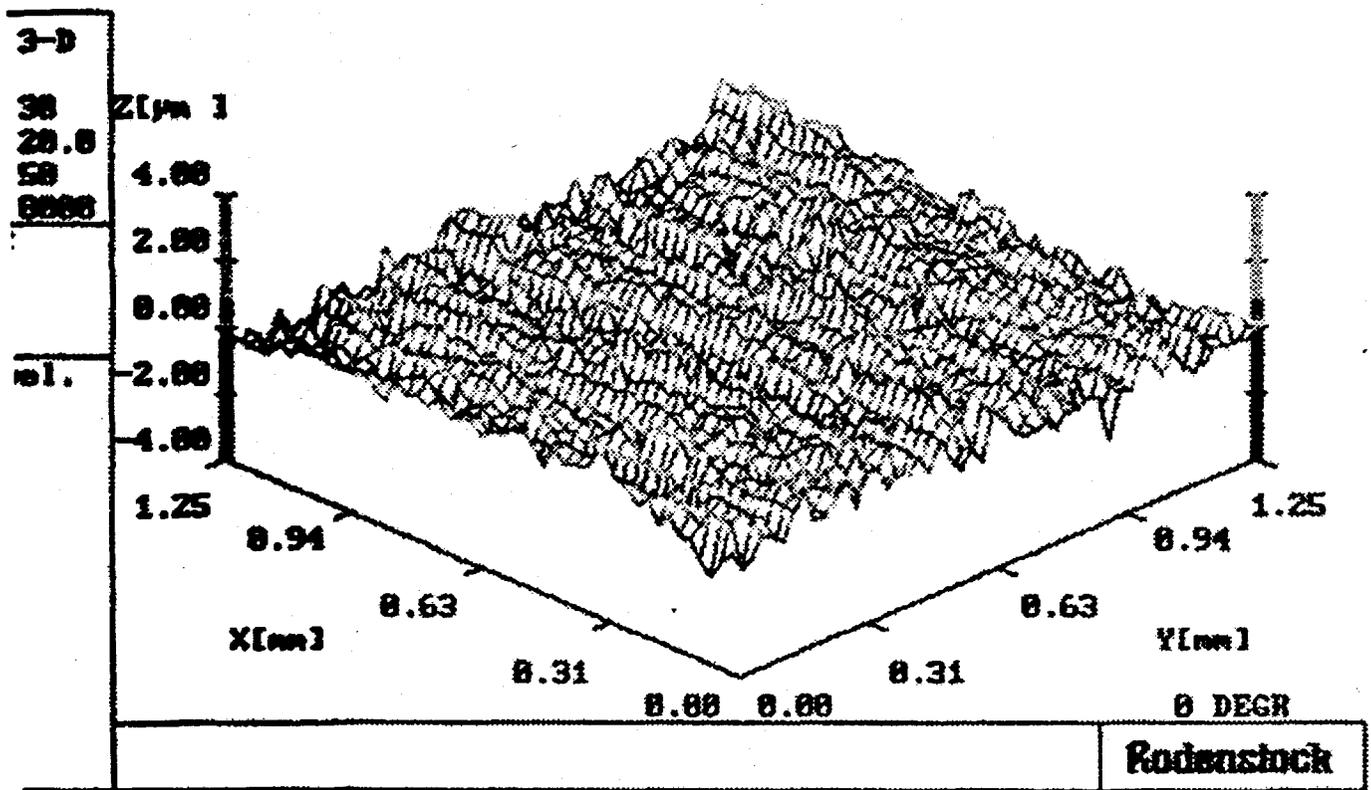


Figure 8. Illustration of the output the non-contact device.

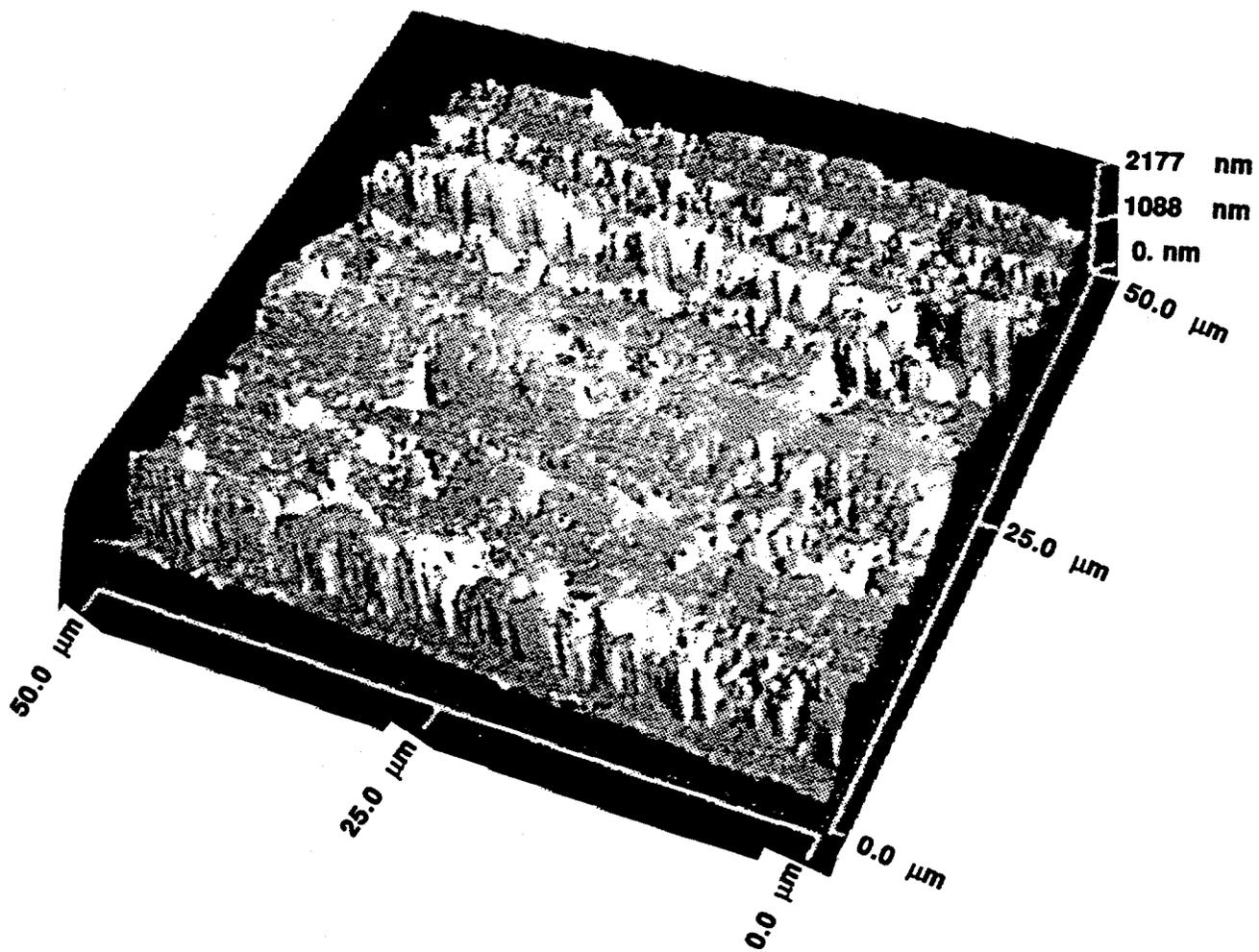


Figure 9. Typical 50 x 50 μm area imaged by the AFM using the normal tip.

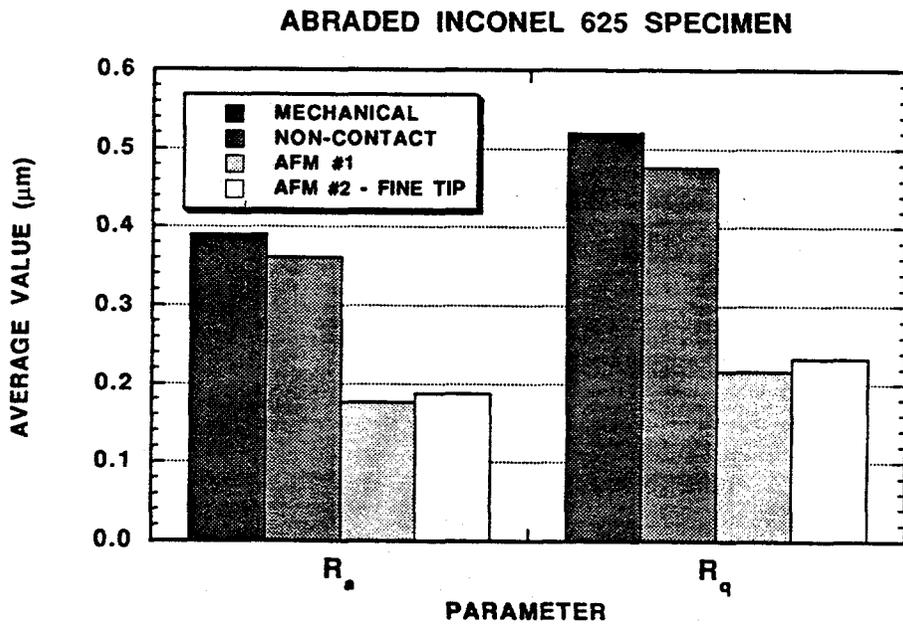
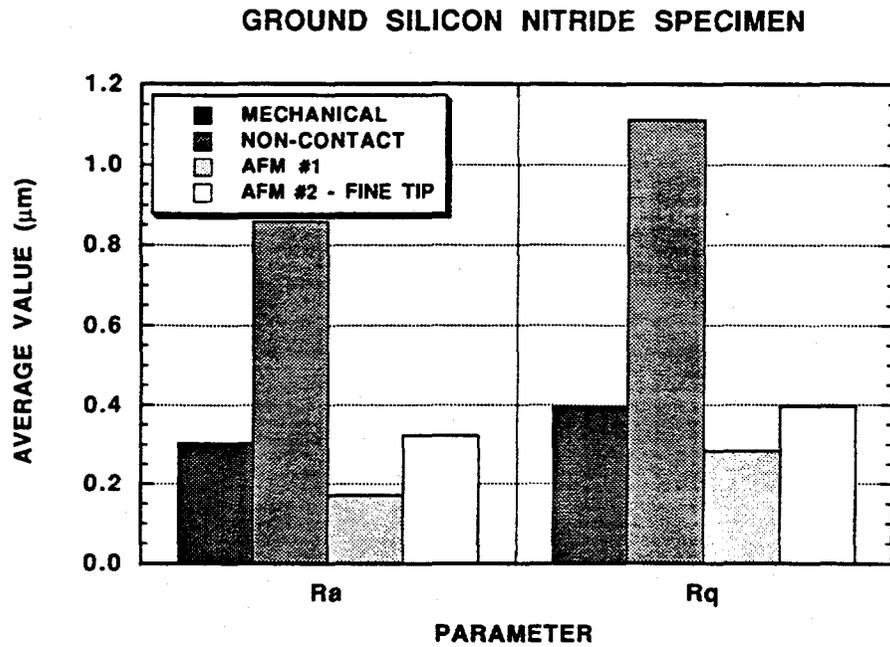


Figure 10. R_a and R_q results from four instruments on the ceramic (a) and metal (b) specimens.

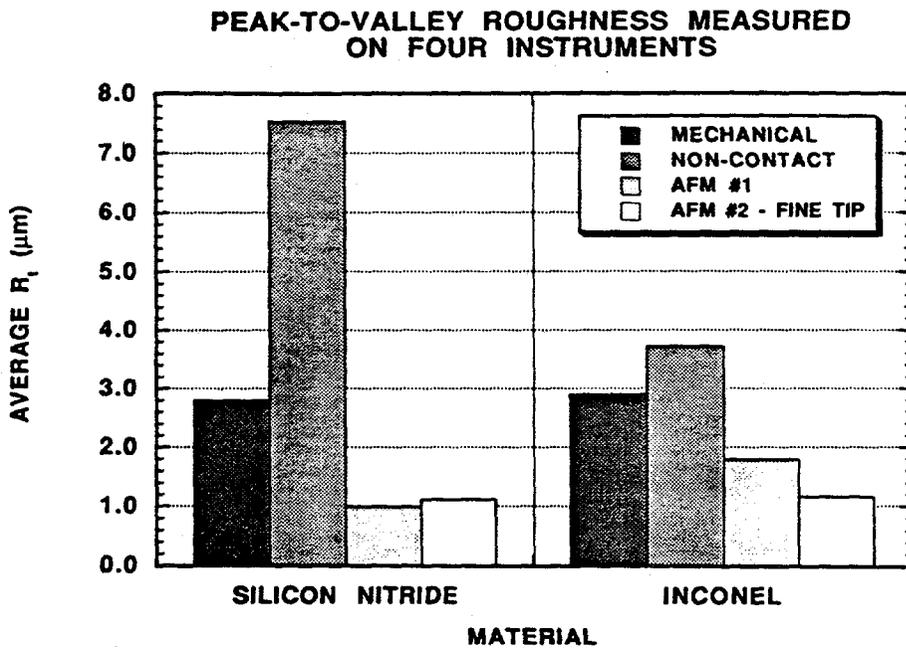


Figure 11 R_t data for both materials.

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