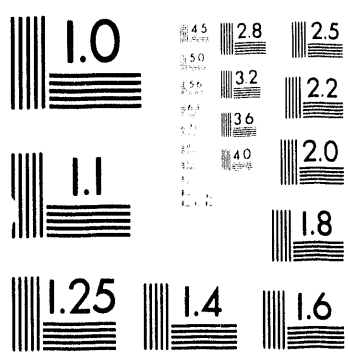
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1 of 1

ION BEAM MILLING OF SILICON CARBIDE OPTICAL COMPONENTS

K. W. Hylton, C. L. Carnal, J. R. Jackson, and C. M. Egert

Optics Manufacturing Operations Development Integration Laboratory
Oak Ridge National Laboratory*
P.O. Box 2009, Oak Ridge, TN 37831-8039
(615) 574-9410, FAX (615) 574-9407

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Optics Manufacturing Operations Development Integration Laboratory
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ABSTRACT

Silicon carbide (SiC) is emerging as an important ceramic material for optical applications requiring stiff, lightweight structures with good thermal conductivity. This report discusses the application of ion milling in the fabrication of SiC optical components. Ion beam milling combined with either ductile grinding or polishing provides an excellent approach to deterministic fabrication of SiC optical components. Results of recent roughness evolution studies for SiC samples prepared by several pre-ion milling fabrication processes suggest that ductile grinding and some polishing processes can be used to produce low-subsurface-damage components suitable for ion milling. Results are also presented of experiments in which these processes have been used in conjunction with ion milling to figure SiC optical components. Typical improvements with optical figures after ion milling have convergences on the order of 2 or 3. Overall, these experiments indicate that ion milling combined with other fabrication processes represents a viable, highly deterministic approach to producing high-precision SiC optical components.

1. INTRODUCTION

Ion beam milling is an advanced optical fabrication process that offers a viable alternative to mechanical polishing. Mechanical polishing requires many iterations of polishing and measuring the surface to achieve figure accuracies on the order of hundreds of angstroms. Each iteration is time-consuming and costly. However, ion beam milling is a highly deterministic fabrication process. A predictable amount of material is removed; hence, as little as a single iteration is needed to achieve the desired final surface accuracy, saving both time and money.

Because ion beam milling applies no mechanical force to the optic being milled, fixturing the part is greatly simplified. Unlike mechanical polishing, ion beam milling produces no edge roll-off or difficulty in corners and is therefore applicable to unusual component shapes. An additional benefit is that the process yields a final surface that is atomically clean, making it possible to coat in the same chamber used for milling. This capability makes the process even more economical.

Because ion beam milling removes material in extremely small quantities, the optic must first be prepared by polishing, diamond turning, or ductile grinding. If the ion beam milling process is used to remove larger amounts of material, it may uncover subsurface damage if present in the surface. The ion milling process itself does not cause subsurface damage in SiC; rather, it simply uncovers subsurface damage already present as a result of other fabrication processes. When ion beam milling is used on prepolished chemical vapor deposited (CVD) SiC optical components, the process uncovers minor subsurface damage but is able to accurately figure optics.

CVD SiC is emerging as an important ceramic material for optical applications requiring lightweight, stiff structures with good thermal conductivity. CVD SiC thermal conductivity is 250 W/m·K, and other glass ceramics are on the order of only 1-6 W/m·K. CVD SiC is well suited for many applications such as in the space and microelectronics industries. The Optics Manufacturing Operations Development and Integration Laboratory (MODIL) ion milling efforts have resulted in the successful figuring of CVD SiC flats and spheres.

2. EQUIPMENT LAYOUT

A 1.2-m-diam cylindrical vacuum chamber with an operating pressure of 10^{-7} torr was used for the experiments. A 3-cm ion source with 1.7-cm collimating grids was used to remove atoms of material from the surface of an optic. Greater detail on the experimental apparatus and the ion milling process is provided in earlier reports.[1] An x-y stage was used to raster the ion source across the surface of the optic, dwelling at predetermined times based on Carnal's singular value deconvolution algorithm.[2] Each dwell time corresponds to a material removal amount. Simulations of the material removed and the final surface after ion beam milling have been developed to validate the ion milling process. The simulated final figure is compared to the actual final figure to verify the deterministic nature of ion milling and to verify that milling parameters remain constant throughout the ion milling run. An argon ion beam was used in these experiments, with operating parameters of 750 V and 15 mA chosen for stable operation at a distance of 11.4 cm from the optic. Stability and accurate characterization of the ion beam are required to produce a high-figure-quality optic.

3. BEAM CHARACTERIZATION

Several recent developments in ion beam characterization have resulted in more repeatable ion beam milling results. A current probe was installed in the vacuum chamber to monitor beam current density to ensure beam stability. In addition, a back plate was installed on the optic holder to provide a uniform target surface for the ion beam. This plate helps maintain stable beam characteristics. Another important recent development is the use of new methods for determining the beam profile.

The traditional method for obtaining a beam profile includes measuring a second optic of the same material that is to be ion milled with an interferometer before and after milling. However, interferometry is difficult to use for this application; to obtain accurate results, large near-optical flats of the same material that is to be milled are required. The optic must be precisely aligned by pixels, and a subtraction of before and after phase maps must be performed to calculate the material removal rate. This approach is time-consuming, tedious, and expensive. Figure 1 shows a flow chart of the ion beam milling process employing the traditional method of obtaining beam profiles.

A combination of step profilometry and current probe measurements provides a simple and accurate alternative means of measuring beam profiles. In this process, a coupon partially covered by a mask is milled. The maximum depth of the beam is determined by measuring the step change on the masked coupon, and a current probe is used to determine the ion beam spread (Fig. 2). As Fig. 3 shows, agreement is good between step profilometry and probe current density. As Fig. 4 illustrates, a beam spread of 1.7-cm collimating grids from a 3.0-cm ion source is constant over varying distances from the current probe. Comparison of a normalized step profile and a current density profile shows that probe current density can be used to calculate beam distribution. The beam characteristics are well defined and therefore can be used to calculate a beam profile from step-profile and current probe measurements.

A modified Gaussian function, referred to as super-Gaussian, was used to generate the beam removal profile:

$$Ae^{-\left|\frac{x}{\sigma}\right|^{c}},$$

where A is the amplitude, σ is the standard deviation, c is the super-Gaussian coefficient, and x is the distance from the center of the beam. The super-Gaussian equation is used instead of a conventional Gaussian equation because the actual beam can have a broader peak than that of the Gaussian curve. Modifying the Gaussian exponent (to form a super-Gaussian equation) generates a wider and more realistic curve. A similar method was used by Allen to ion mill the Keck telescope segments.[3]

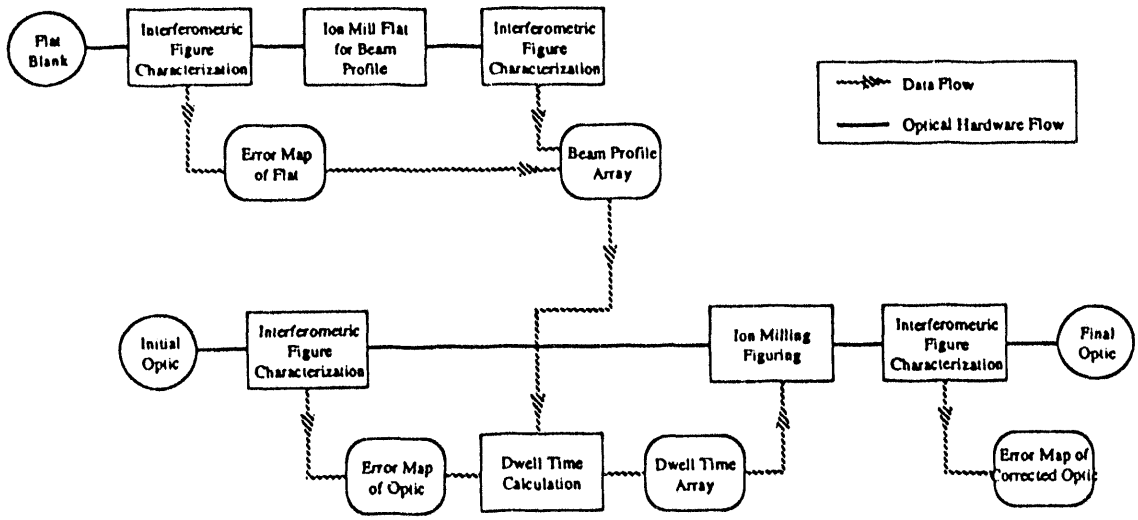


Fig. 1. Flowchart of the ion milling process for optical figure correction.

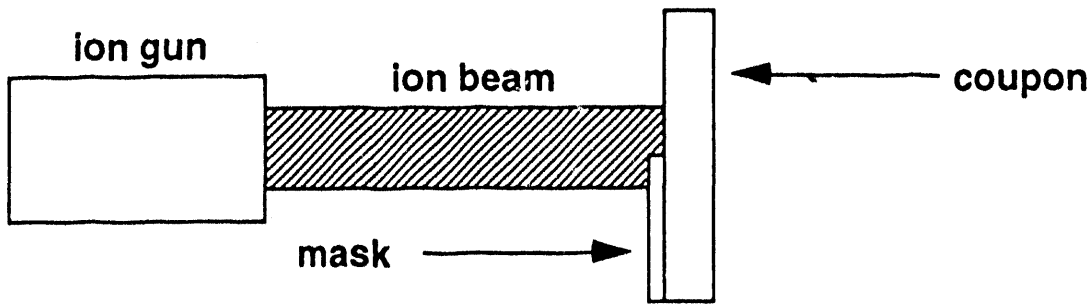


Fig. 2. Ion milling setup with a mask over a portion of the coupon.

The step profilometry/current probe approach to generate beam profiles offers a number of advantages over the method previously used. The new approach drastically reduces the time required to generate a beam profile because the part is measured only one time—after it is milled. The step profilometry/current probe approach offers another advantage—the accuracy of the profile is greatly improved because noisy data are not used. The peak of the beam is found by using step profilometry, and the remainder of the curve is calculated. This process is much simpler than other methods because a current density measurement for a given target distance is obtained one time and may then be used for any material. Finally, this method employs small, inexpensive coupons and eliminates the need for optical flats. Figure 5 shows the flow chart for the simplified ion milling process using the step profilometry/current probe approach to generate beam profiles.

4. MILLING RESULTS

CVD SiC flats and spheres were milled by using the new beam profile method. CVD SiC 40-mm coupons were selected to obtain a beam profile, and two 15.2-cm-diam spheres (r_c = 106.7 cm) were milled, as well as one 10.2-cm-diam flat. Figure 6 illustrates the results of a 9-h run performed on one of the 15.2-cm-diam spheres. Before the run, the peak-valley (P-V) error was 0.248 wave (wave = 0.6328 μm). After the run, the P-V error had been reduced to 0.191 wave, with a convergence of 1.36. Convergence is defined as the ratio of P-V error before and after a single ion milling run.

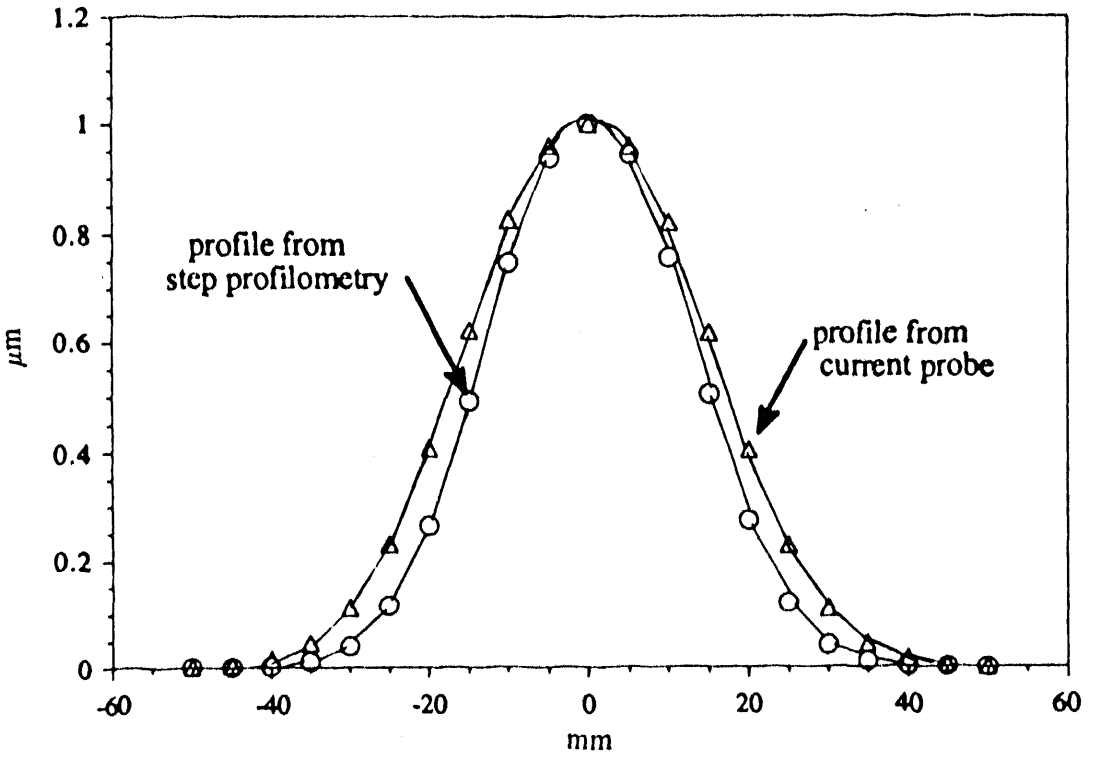


Fig. 3. Normalized step profile and current density profile comparison.

Figure 7 shows the results of a 6-h run performed on another 15.2-cm-diam sphere. The P-V error before the run was 0.891 wave, but by the end of the run it had been reduced to 0.393 wave, with a convergence of 2.18. Over 95% of the surface, a P-V error of 0.18 wave was achieved, and the simulated final surface had a P-V error of 0.21 wave. These results confirm that the final surface can be accurately predicted.

Figure 8 shows a 10.2-cm flat with a hole in the center; this flat was previously used for obtaining a beam profile by the conventional method. The purpose of the experiment was to remove the beam profile from the optic. This was a difficult task because of the high slope of the beam profile; ion beam milling is most effective when the workpiece has low spacial frequency errors. The optic had previously been ion milled to partially remove the beam profile. The run time in Fig. 8 was 16.2 h, and the P-V error before the run was 0.502 wave. After the run, the P-V error had decreased to 0.19 wave, and the convergence was 2.6.

Figure 9 illustrates the second pass of the optic shown in Fig. 8. The first pass was used to remove enough material to lower the P-V error to a level that could be milled to a high figure accuracy in a few hours. Figure 9 shows that the run was 7 h, and the P-V error at the beginning of the run was 0.19 wave. After milling, the P-V error had dropped to 0.16 wave, and the P-V error was 0.065 wave over 90% of the surface. These results indicate that it is possible to achieve final figures with P-V errors of 0.05 wave. The convergence over 90% of the surface is 2.8. Although convergences on the order of 2 or 3 have been consistently achieved over several ion milling runs, the goal is to achieve convergences on the order of 4 or 5.

5. FINISH QUALITY

Initial results indicate that using the ion milling process did not significantly degrade the finish quality. One part was measured before and after milling, and those measurements indicated a change from 10 Å root mean square (RMS) roughness to 15 Å RMS roughness. Various commercially available polishing processes produce different roughness evolution results, as Fig. 10 illustrates.[4] Ductile-ground CVD SiC is compared with two different

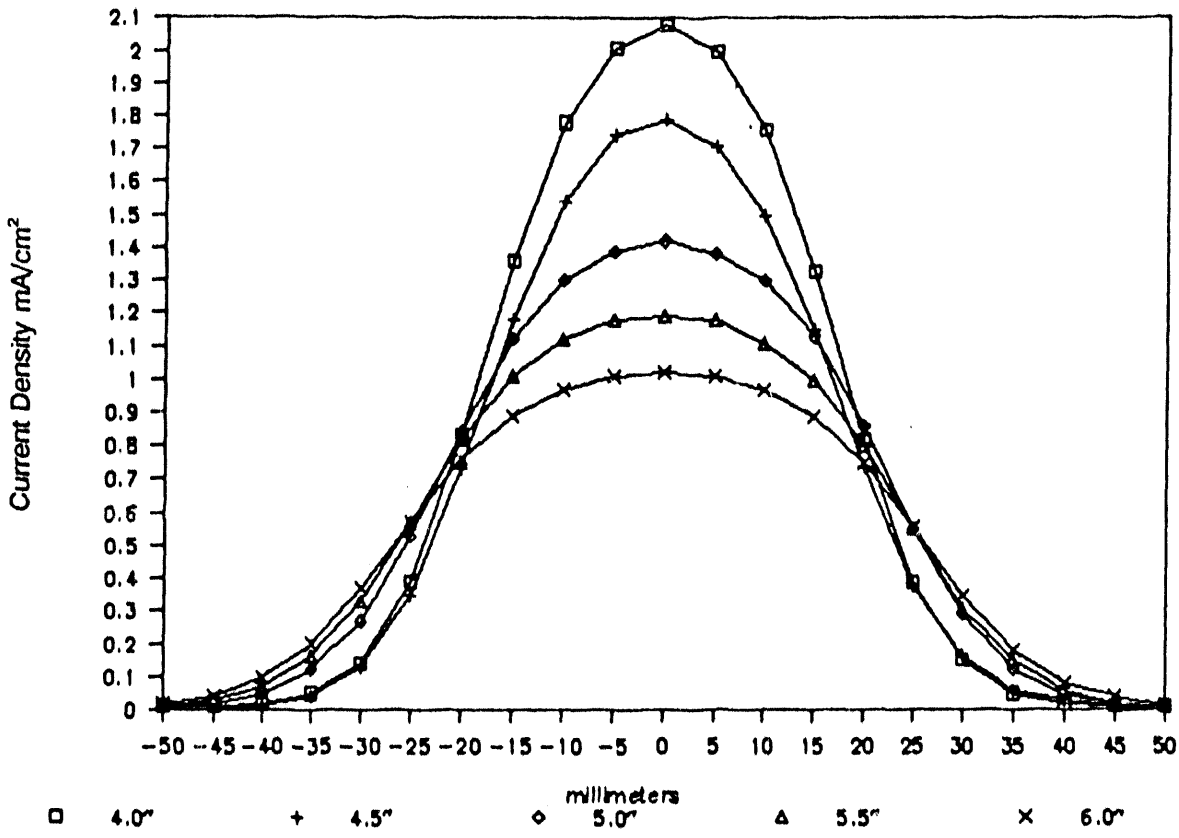


Fig. 4. Beam spread of 1.7-cm collimating grids [current density at 4, 4.5, 5, 5.5, and 6 in. (10.16, 11.43, 12.7, 13.97, and 15.24 cm)] from the current probe (750 V, 15 mA).

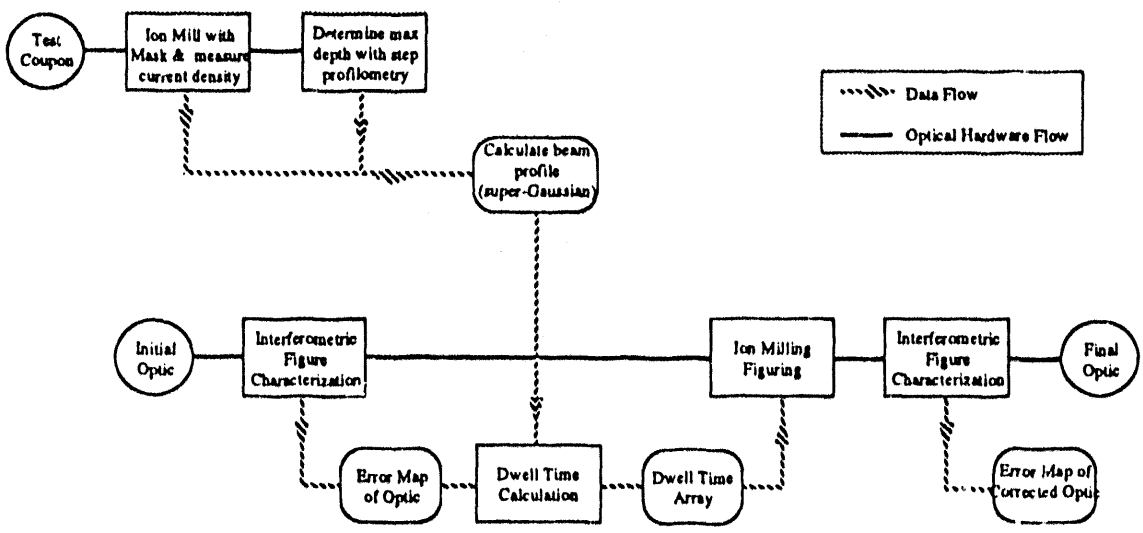


Fig. 5. Flowchart of the modified ion milling process for optical figure correction.

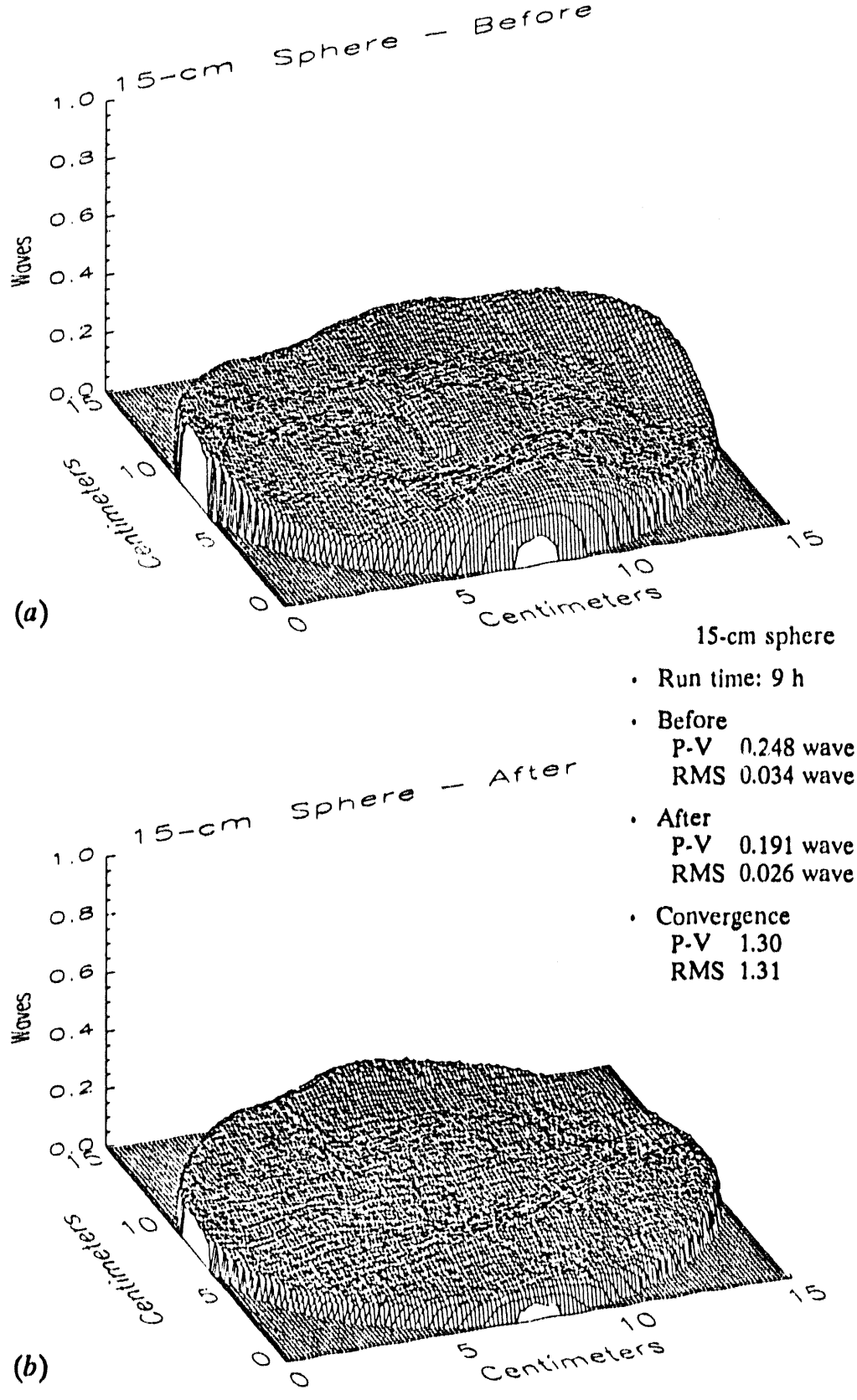
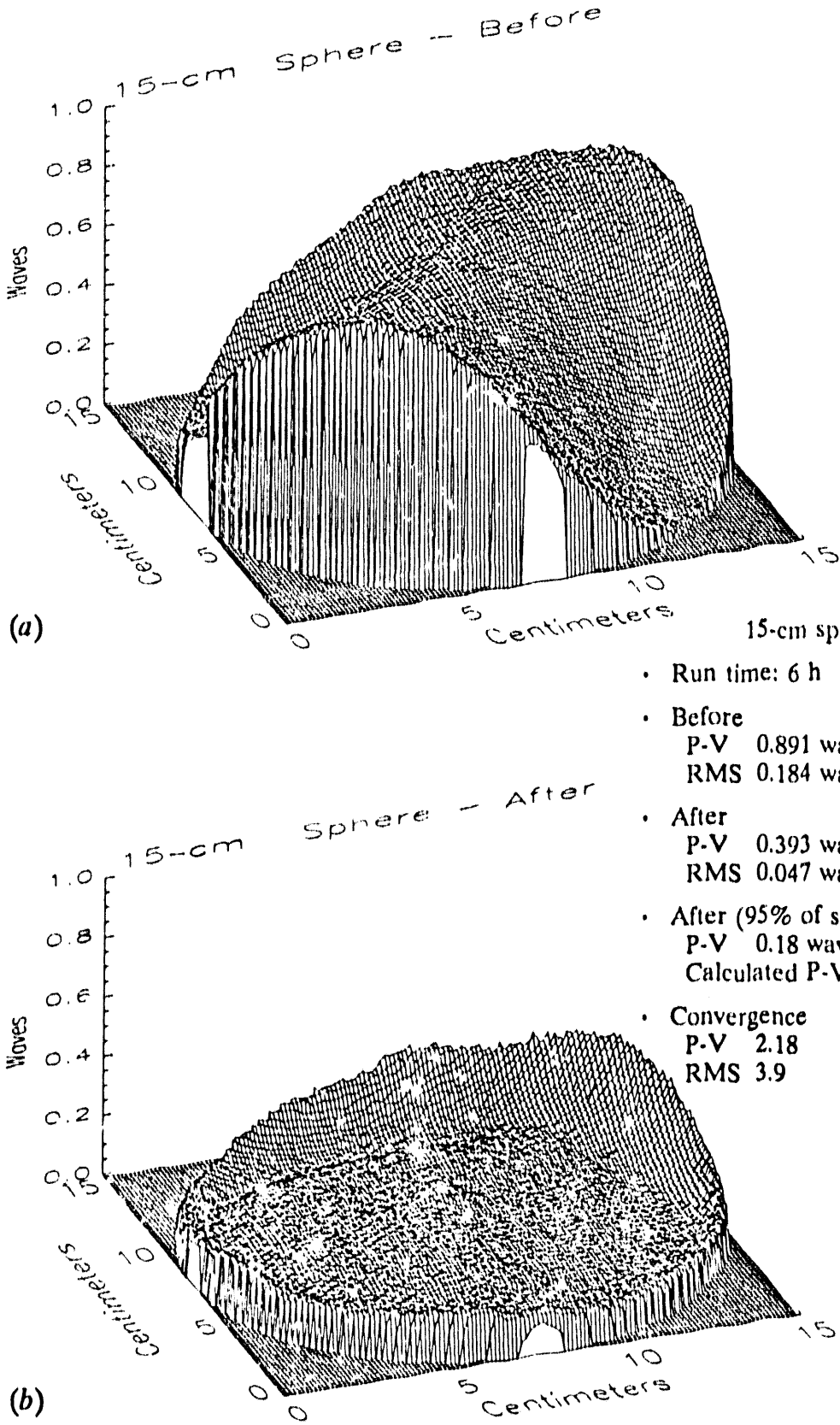


Fig. 6. Phase map of 15-cm-diam chemical vapor deposited silicon carbide sphere (*a*) before 9-h run, (*b*) after 9-h run (P-V = peak-valley, RMS = root mean square).



15-cm sphere

- Run time: 6 h
- Before
  P-V 0.891 wave
  RMS 0.184 wave
- After
  P-V 0.393 wave
  RMS 0.047 wave
- After (95% of surface)
  P-V 0.18 wave
  Calculated P-V 0.21 wave
- Convergence
  P-V 2.18
  RMS 3.9

Fig. 7. Phase map of 15-cm-diam chemical vapor deposited silicon carbide sphere (*a*) before 6-h run, (*b*) after 6-h run (P-V = peak-valley, RMS = root mean square).

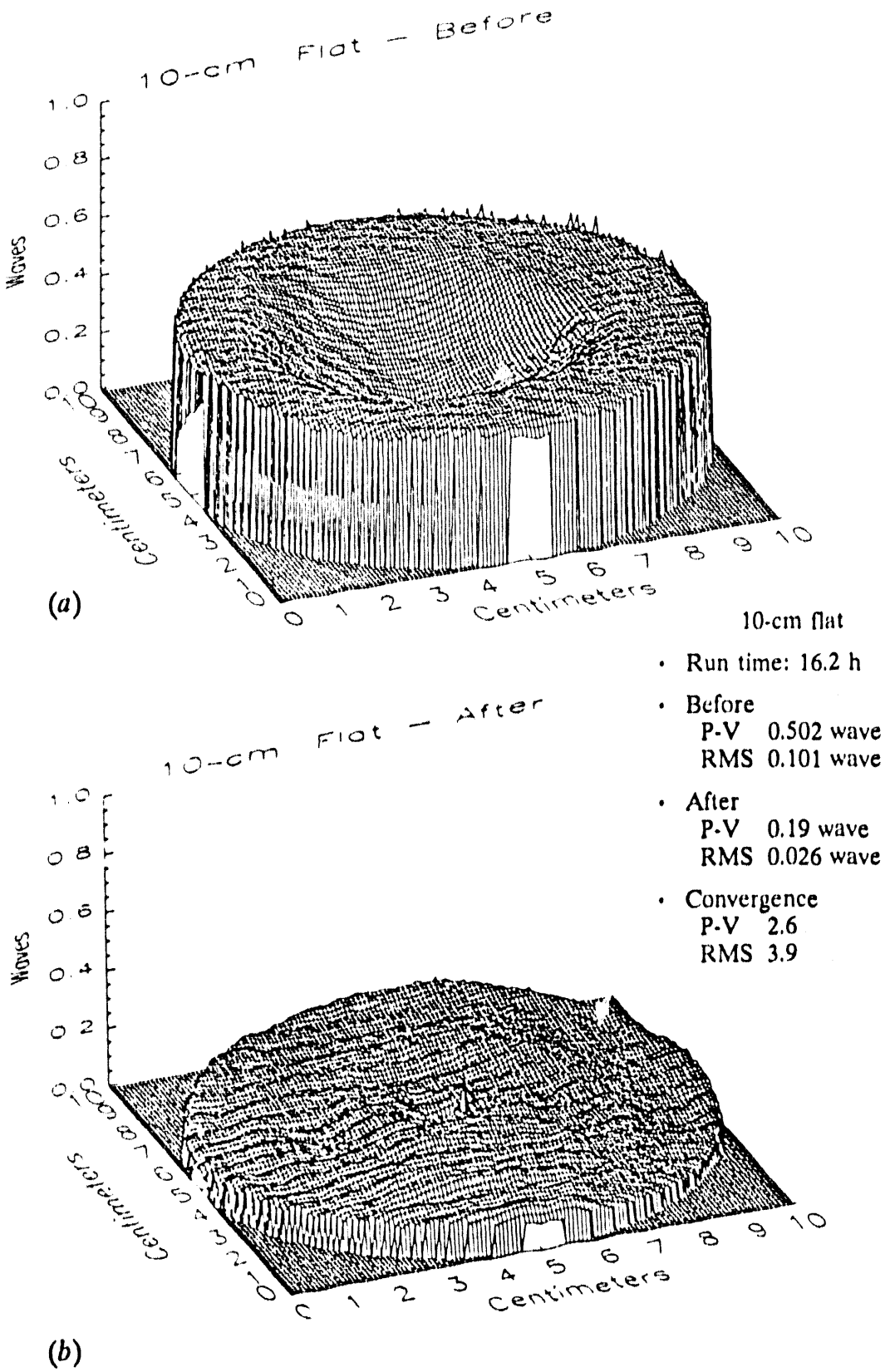


Fig. 8. Phase map of 10-cm-diam chemical vapor deposited silicon carbide flat (*a*) before 16.2-h run, (*b*) after 16.2-h run (P-V = peak-valley, RMS = root mean square).

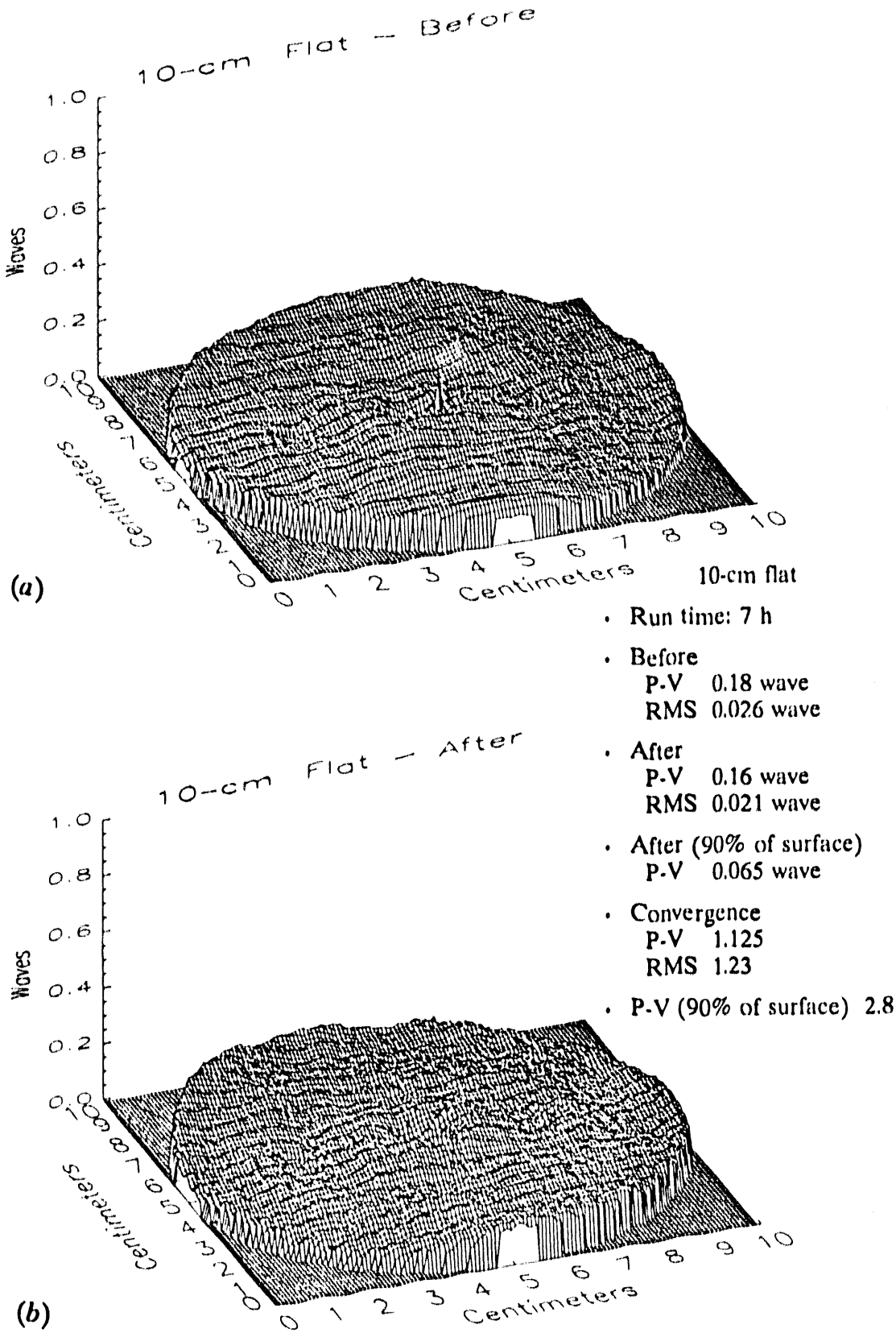


Fig. 9. Phase map of 10-cm-diam chemical vapor deposited silicon carbide flat (*a*) before 7-h run, (*b*) after 7-h run (P-V = peak-valley, RMS = root mean square).

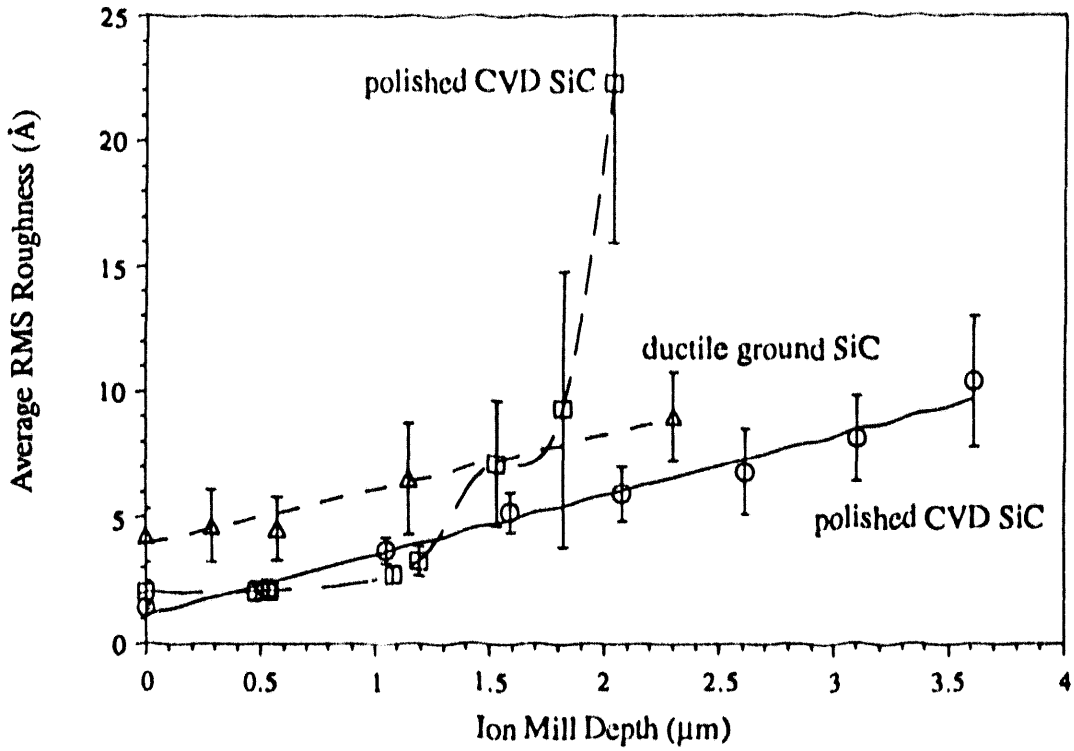


Fig. 10. Roughness evolution results from different commercially available polishing processes (CVD = chemical vapor deposited silicon carbide, RMS = root mean square, SiC = silicon carbide).

polishing techniques for CVD SiC. For ion milling depths of up to ~1 μm, each of the materials roughened only slightly, each being below 5 Å RMS roughness. At 1-2-μm milling depths, the ductile-ground and one of the polished samples became slightly rougher, with RMS roughness measurements remaining at less than 10 Å. The third sample significantly roughened at 1.7-μm milling depth and continued exponentially up to 2 μm with an RMS roughness value > 20 Å. This comparison shows that different polishing processes produce different roughness evolution results. The third sample, which roughened after 2 μm of material removal, was polished in such a manner to cause extensive subsurface damage. Ion milling of CVD SiC does not roughen the part but can uncover subsurface damage if introduced by other fabrication processes.

6. CONCLUSIONS

Experiments with CVD SiC indicate that it can be ion milled for optical figure correction without degrading finish quality. The 10.2-cm-diam CVD SiC flat was ion milled to near 0.05 wave P-V over 90% of the part. The only residual errors in the part were higher frequency errors that are very difficult to remove with ion beam milling. The 15.2-cm-diam spheres were milled to ~0.2 wave P-V. It was determined that the profilometry/current probe approach is a good way to obtain a beam profile. Clearly, the polishing method determines finish quality.

The profilometry/current probe approach to obtain beam profiles has been crucial in the effort to develop ion milling. Highly accurate and precise beam profiles are essential to ion milling algorithms and process controls. Coupling these improvements of ion milling with on-process coating and figure metrology capabilities will lead to reduced operating costs and increased productivity.

7. ACKNOWLEDGMENTS

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