AFWL-TR-87-30

AFWL-TR-87-30

LASER MATERIALS INTERACTIONS RESEARCH

Michael Bass

University of Southern California
University Park
Los Angeles, CA 90089-1112

July 1988

Final Report

Approved for public release; distribution unlimited.

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117-6008

AFWL-TR-87-30

This final report was prepared by the University of Southern California, Los Angeles, California under Contract F29601-85-K-0117, Job Order 22180202 with the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico. Captain Jerry R. Couick (TALE) was the Laboratory Project Officer-in-Charge.

This technical report has been reviewed and is approved for publication.

Jerry R. Couick

JERRY R. COUICK
Captain, USAF
Project Officer

FOR THE COMMANDER

Jorge E Beraun

JORGE E. BERAUN
Chief, Directed Energy Effects Br

Thomas J. Settecerri

THOMAS J. SETTECERRI
Lt Col, USAF
Chief, Lethality Assessment Division

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFWL-TR-87-30
6a. NAME OF PERFORMING ORGANIZATION University of Southern California 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Weapons Laboratory
6c. ADDRESS (City, State, and ZIP Code) University Park Los Angeles, California 90089-1112	7b. ADDRESS (City, State, and ZIP Code) Kirtland Air Force Base, NM 87117-6008
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-K-0117
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 62601F; PROJECT NO. 2218; TASK NO 02; WORK UNIT ACCESSION NO. 02

11. TITLE (Include Security Classification)
LASER MATERIALS INTERACTIONS RESEARCH

12. PERSONAL AUTHOR(S)
Bass, Michael

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM Aug 85 TO Aug 86	1988 July	40

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
08	03	
20	01	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Surface waves, Coupling, Energy redistribution, Ripples, Acoustic waves, Grating, Unipolar arc, Plume, Propagation, Plasma, Electric field,

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report examines the role of surface electromagnetic waves (SEWs) in laser material interaction scenarios. It is felt that, in some instances, the SEWs greatly enhance the coupling of intense laser light to materials, especially metals. Experiments were performed to determine the amount of energy redistribution via SEWs outside the irradiated area. The data obtained in these experiments suggest that SEWs are not a significant source of enhanced coupling of laser light to materials. The possibility exists, however, that the experimental setup was incapable of providing information contradicting this observation. Future experiments will clarify this issue. The report also examines the role of plasma formation in enhanced coupling. Experimental results indicate that unipolar arcing may be a major source of enhanced coupling.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL JERRY R. COUICK, Capt, USAF	22b. TELEPHONE (Include Area Code) (505) 844-4712 — 22c. OFFICE SYMBOL TALE

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

CONTENTS

LIST OF FIGURES

Figure (Cont'd) Page

1. INTRODUCTION

1.1 Research in this program was concerned with the processes of interaction between intense laser light and materials. The major areas of interest during the first year were the interactions between laser-generated plasmas and surfaces and the processes of interaction with surface electromagnetic waves (SEW). Laser-generated plasmas can either couple or decouple incoming energy from the material. One proposed interaction which would couple energy to the surface is the formation of unipolar arcs. This process would be discerned by a residual morphology showing small craters related to the sites of unipolar arc formation in the area covered by the plasma. Experiments to confirm this process on copper samples were carried out and the predicted craters were found.

1.1.1 The first interest in the SEW studies was to demonstrate that SEW interactions could play a role in coupling light energy to a variety of materials, not just metals. Studies of this phenomenon were conducted on plastic and mullite targets. The mullite had a molten phase upon laser irradiation. However, the process of melting and resolidification was too violent to allow postirradiation detection of the grating like structures thought to be caused by SEWs. Ripples on mullite or other such materials may be discovered by probes to detect diffraction from the gratings during the irradiation. The plastic, ordinary acrylic, was too transparent to allow irradiations affecting only the surface. This meant that irradiation conditions were used which produced catastrophic fracturing and blowing off of surface material or bulk damage. The former proved uninteresting for this project, but the latter revealed grating like structures in internal damage sites. These are found in laser-produced internal cracks, and they look much like those produced on a surface. However, their spacing and orientation with respect to the laser polarization is different from site to site. This observation requires a great deal more study.

1.1.2 Grating like structures were observed in the periphery of interaction sites produced on Al, Cu and the alloy Ti-6 Al-4 V. The interaction in the central region (where convective motion of the melt and boiling took place) so disrupted the material that no grating like ripples could be found in the central site morphology.

1.1.3 The second aspect of SEW interactions was the question of energy redistribution because of their propagation out of the irradiated spot. This had been predicted by researchers in Romania and the Soviet Union. It was thought to be the source of a spot size dependence to laser materials interactions and, as such was of great interest to this program. An experiment using a photothermal probe of localized surface heating was developed to enable a direct *measurement of the propagation of SEWs.* (This represents the first attempt to directly observe SEW and not just infer their effects on the basis of postirradiation site morphology.) This experiment depended upon the change in reflectivity of the sample induced by heating at the surface as the SEW passed by. No evidence for SEW related energy redistribution was found in experiments on aluminum irradiated at 1.06 um.

1.1.4 In preparation for continued work a Nd:glass laser oscillator-amplifier system was installed and the first three stages operated. Over 3 J/Pulse in 30 ns flat topped pulses have been obtained. Also, to allow experiments at shorter wavelengths, optical second, third and fourth harmonic generators have been obtained for this laser system.

2. PROGRESS AND RESULTS

2.1 Facilities Preparations. During the first year of this project, one task was to install and operate the Nd:glass laser oscillator-amplifier system and the irradiation facilities for future work at 1.06 um and other wavelengths. The oscillator and two amplifiers have been operated and over 3 J have been obtained. The pulse duration is 30 ns and the beam distribution is flat topped. Some problems of aperture induced diffraction were encountered and steps are being taken to eliminate this by relocating the mode determining aperture further from the amplifiers. The third and fourth amplifiers and the Faraday isolator are being installed to allow operation at 30 J at 1.06 um.

2.1.1 To enable operation at 0.53, 0.35 and 0.26 um optical second, third and fourth harmonic generators have been purchased. These are being tested and aligned for use with the Nd:glass laser system.

2.1.2 Two chambers have been prepared for use in the second and third years' work. One is a Plexiglass chamber for use at fore pump vacuums and the other is a six ported glass chamber for operation at higher vacuums. A new flange assembly had to be designed for the glass chamber to minimize the risk of cracking the chamber when changing windows or other flange mounted apparatus.

2.1.3 A high energy capacity joule meter and other necessary beam and interaction diagnostics are on hand.

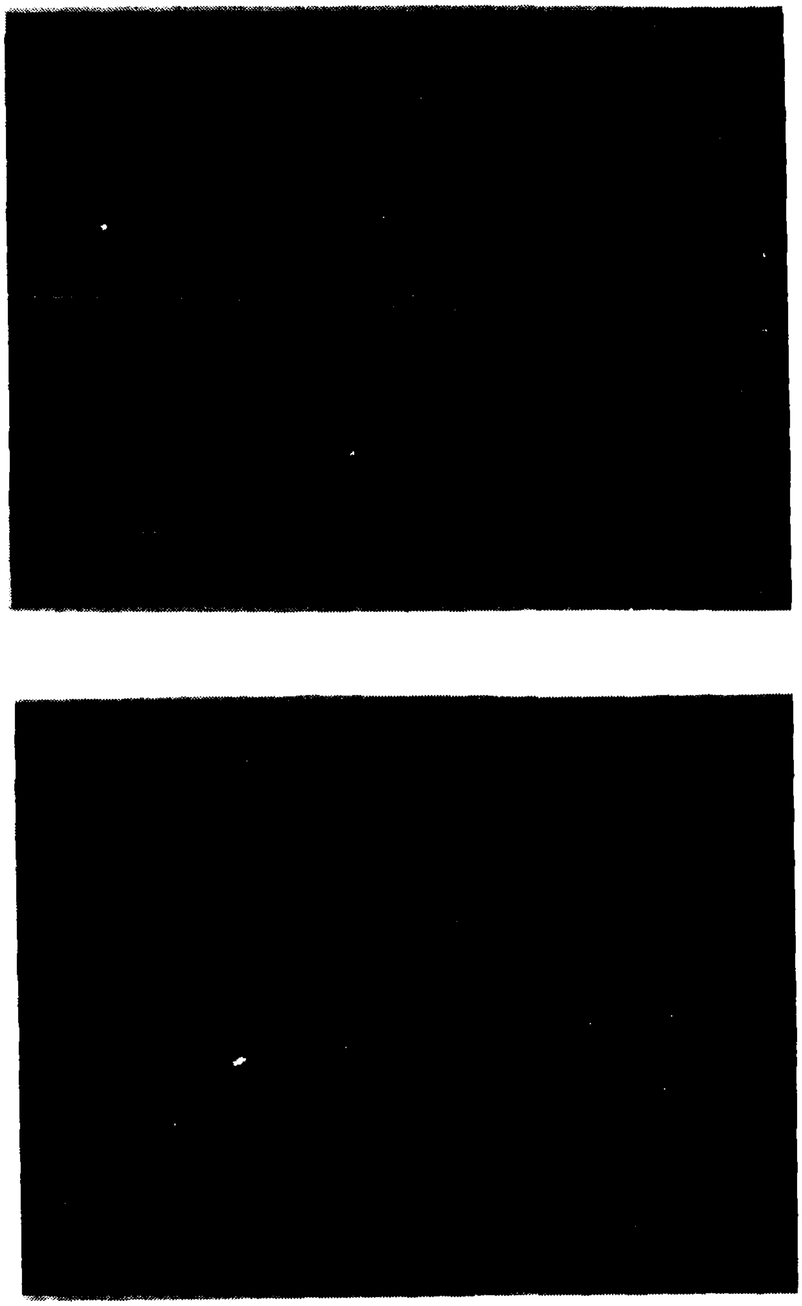
2.2 <u>Evidence for Unipolar Arcs</u>. A variety of plasma-driven interactions have been proposed over the years which can either increase the coupling of laser light to materials or which can decouple incoming light from the sample. One, which is independent of the presence of an atmosphere and which takes place whether or not the light field is present over the material is the formation of unipolar arcs (Ref.1). The laser light is absorbed by the material and heats, melts, boils and vaporizes it if necessary to produce a vapor. This vapor becomes ionized by multiphoton or thermal processes and a plasma is produced over the surface of the target. Because of the different mobilities of electrons and ions in the plasma cloud, larger numbers of electrons return to the surface than ions leaving the plasma at a positive potential with respect to the surface. This potential difference can cause a form of field emission at microscopic surface defects which then form so-called unipolar arcs. The ions are accelerated to the surface and small circular craters are formed. These craters are signatures of the unipolar arc process and their detection would be confirmation of the model. In Reference 1 there are some micrographs purporting to show these craters. Experiments on polished copper samples were undertaken to attempt to independently confirm the presence of unipolar arc craters.

2.2.1 Figures 1 and 2 show the region where craters were detected and close-up scanning electron micrographs of the unipolar arc craters. The area in which craters are found is thought to be outside that irradiated but where the plasma may have spread to during or after the irradiation. The unipolar arc interaction process is independent of the presence of the light and confirmation of this observation by more careful measurements is called for. If confirmation can be obtained then the interaction model will be strengthened and it may be used with more confidence.

2.2.2 Figure 3 shows a comparison of an arc site on the polished copper and a possible arc site on a piece of diamond-turned copper irradiated several years ago at 10.6 um. This suggests that the process of unipolar arcing operates no matter what wavelength laser is used and no matter how well the surface is finished. More data are needed to confirm this point, and it may be useful to retake some of the 10.6 um data.

2.3 SEW Interactions

2.3.1 Energy Redistribution Because of SEW Propagation.



Polished Copper Irradiated at 1.06 μm in Vacuum

167 μm

Region where Arc Sites are Found

16.7 μm

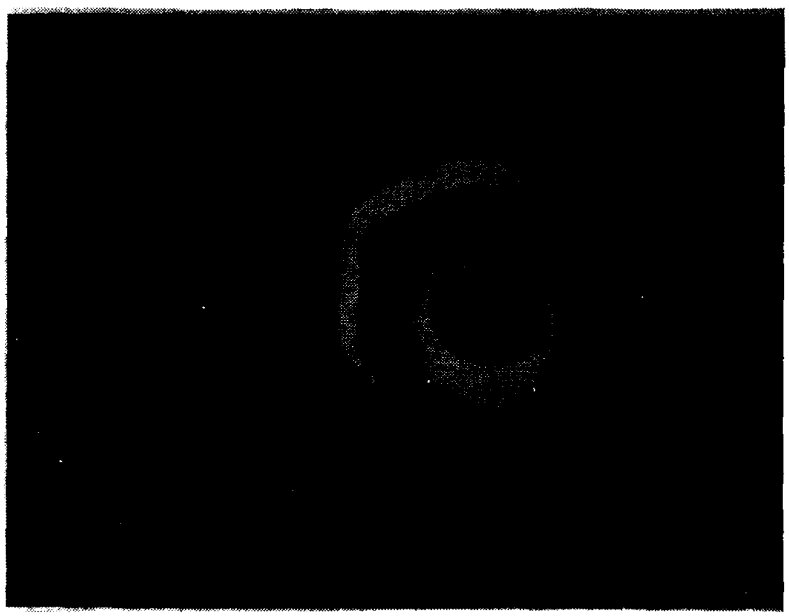
Possibly Sites of Unipolar Arcs

Figure 1. Scanning electron micrographs of the polished copper sample showing sites of unipolar arcs. The 1.06 μm Nd:glass laser was used in this irradiation.

Polished Copper
Irradiated
at 1.06 μm in
Vacuum

3.3μm

Possibly Sites
of Unipolar Arcs



1.67μm

Figure 2. Sites shown in Figure 1 but at higher magnification.

Polished Copper
Irradiated
at 1.06μm in
Vacuum

4μm

SEM Incident at
25° to Normal

Possible Site of
Unipolar Arc

Diamond Turned
Copper
Irradiated at 10.6μm
in Vacuum

4μm

SEM Incident at
≥ 40° to Normal

Possible Site of
Unipolar Arc

Figure 3. Comparison of unipolar arc sites found on the sample in Figure 1 and a site found on a diamond turned copper sample irradiated at 10.6 μm in early work.

An experiment to directly detect SEW propagation and absorbed energy redistribution was performed using a photothermal technique. No evidence for the predicted energy redistribution was found. A paper was submitted for presentation at the 1986 Boulder Symposium on Laser Materials Interactions*.

2.4 <u>The Role of SEWs in Laser Interactions with Metals.</u> A pulsed Nd:YAG laser was used to demonstrate the formation of grating-like ripples in the surfaces of Al, Cu, and the alloy Ti-6Al-4V. These are shown in Figures 4, 5 and 6. In addition to the ripples shown, it is important to notice the other features shown in these scanning electron micrographs. The central region of each material is seen to have been violently disrupted by convective motion of the molten material and by boiling. These macroscopic disruptions eliminate grating-like ripples, which may have been present during irradiation, from the refrozen material's morphology. Thus, it is essential to look for ripples in the outer regions of the site where the other motions are so vigorous that grating-like structures cannot be formed during the irradiation. The implications of this can be explored by monitoring diffraction of a probe beam during the pulse. If there are not grating-like ripples during

----

*A copy is available from R. Swimm, Center for Laser Studies, USC, Los Angeles, CA 90089-1112

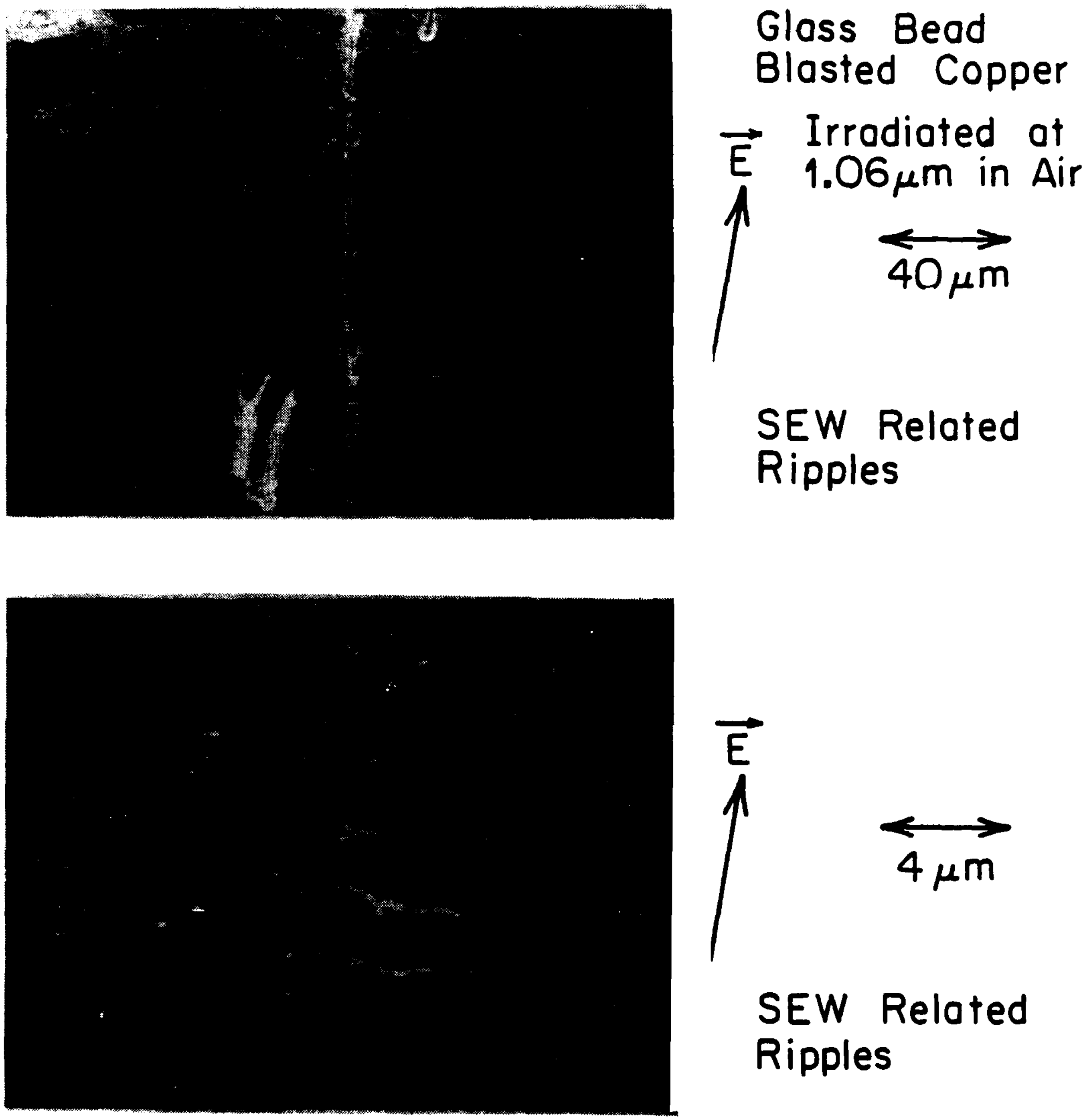
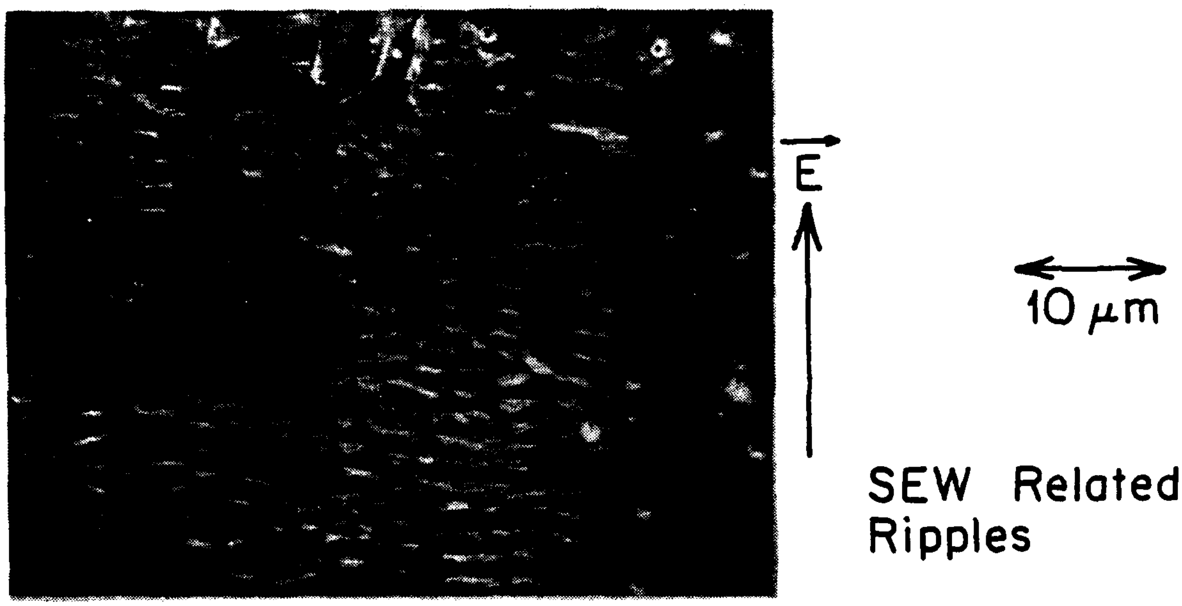
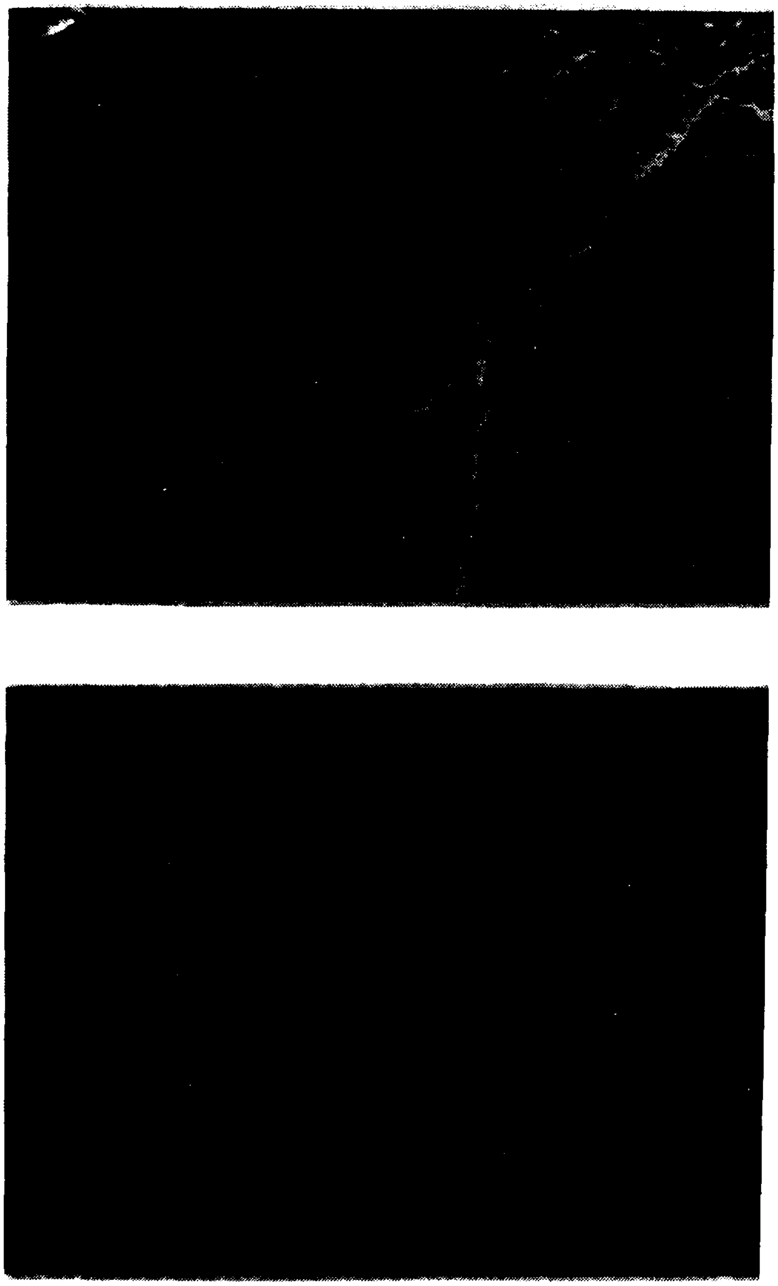


Figure 4. Scanning electron micrographs of the grating-like structure related to surface electromagnetic wave interactions found on glass bead blasted copper. Irradiated at normal incidence, at 1.06 μm in air.



(Cont'd)
Figure 4. Scanning electron micrographs of the grating-like structure related to surface electromagnetic wave interactions found on glass bead blasted copper. Irradiated at normal incidence, at 1.06 μm in air.



Diamond Turned Al
Irradiated at
1.06 μm in Air

42.5 μm

Border Between
Irradiated and
Unirradiated Metal

4.25 μm

SEW Related
Ripples

Figure 5. Scanning electron micrographs of the grating-like structure related to surface electromagnetic wave interactions found on aluminum. Note evidence for boiling in the central area.

4.25 μm

Evidence of Boiling in Central Area

(Cont'd)

Figure 5. Scanning electron micrographs of the grating-like structure related to surface electromagnetic wave interactions found on aluminum. Note evidence for boiling in the central area.

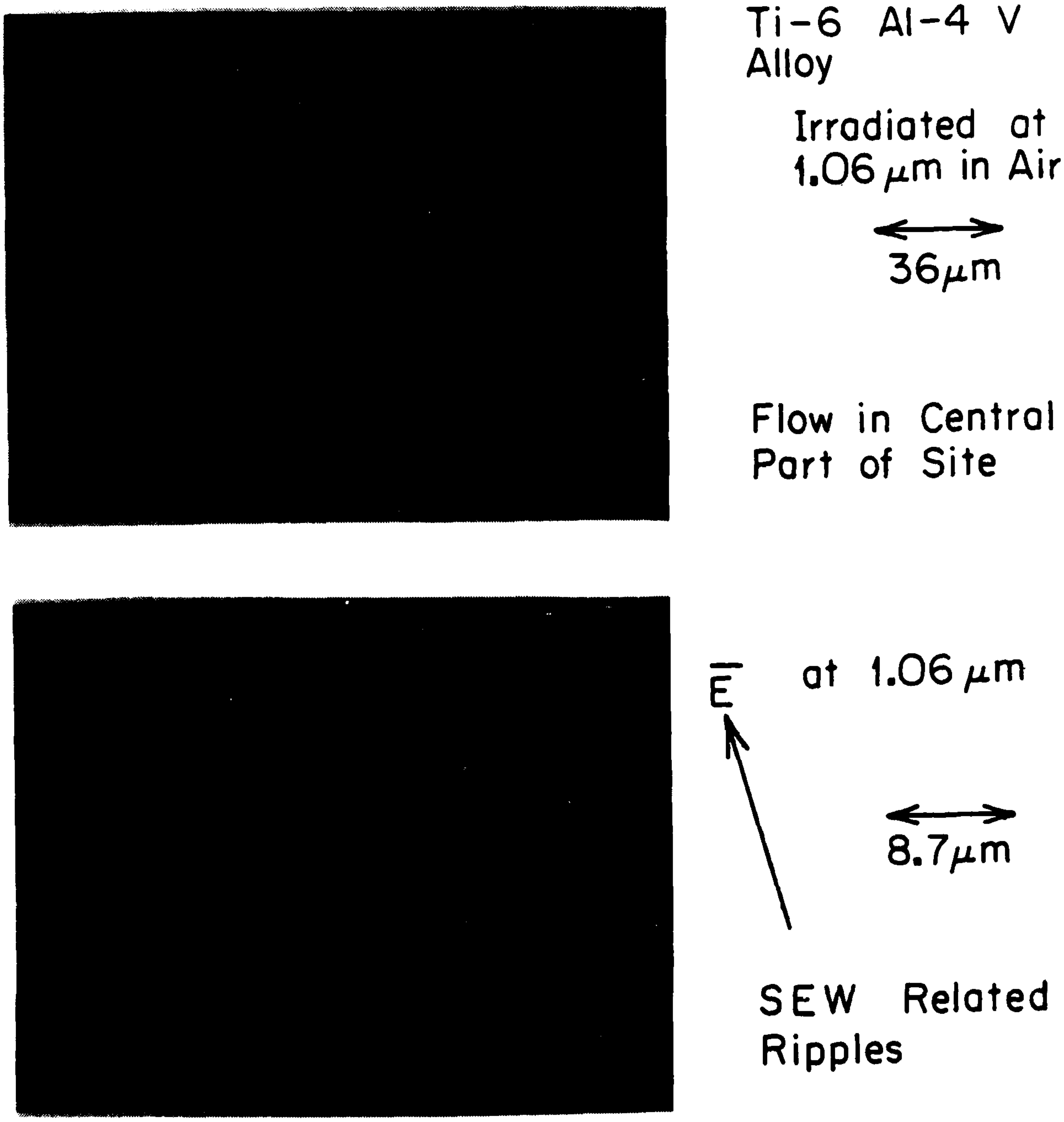


Figure 6. Scanning electron micrographs of the grating-like structure related to surface electromagnetic wave interactions found on Ti-6 Al-4 V alloy. Note the flow of material which can obscure information gained from strictly morphological studies.

36μm

Flow in Central
Part of Site
Obscures Morphology

(Cont'd)
Figure 6. Scanning electron micrographs of the grating-like structure related to *surface electromagnetic* wave interactions found on Ti-6 Al-4 V alloy. Note the flow of material which can obscure information gained from strictly morphological studies.

the irradiation then the proposed additional absorption because of SEWs cannot take place. The effects of SEWs may be masked in high intensity, pulsed laser materials by other, more conventional processes.

2.4.1 In Figure 6, some flow ripples are shown to indicate the potential difficulty which might be encountered in trying to identify grating-like structures. The SEW related structures are generally quite linear and oriented perpendicular to the light polarization vector. The flow ripples are curved and do not have any particular orientation with respect to the light polarization. In fact they are oriented more by the shape of the boundary between the melted and the unmelted materials.

2.5 The Role of SEWs on Mullite. Mullite is a ceramic material composed of oxides of Al, Mg and Si. The reflectivity of this material relative to $BaSO_4$ is shown in Figure 7. The strong drop in reflectance at ~340 nm suggests that this material may be more sensitive to laser irradiation with excimer lasers than it is at 1.06 um. In fact, it will be studied with the third harmonic of the Nd:glass laser.

2.5.1 Figures 8 to 12 show the surface of laser irradiated mullite and clear evidence for laser induced melting. The interaction of melting and resolidification is sufficiently vigorous to preclude detection of gratinglike structures in the morphology of the irradiated material. It is possible that such structures are present and experiments using the diffraction of a probe beam during irradiation will

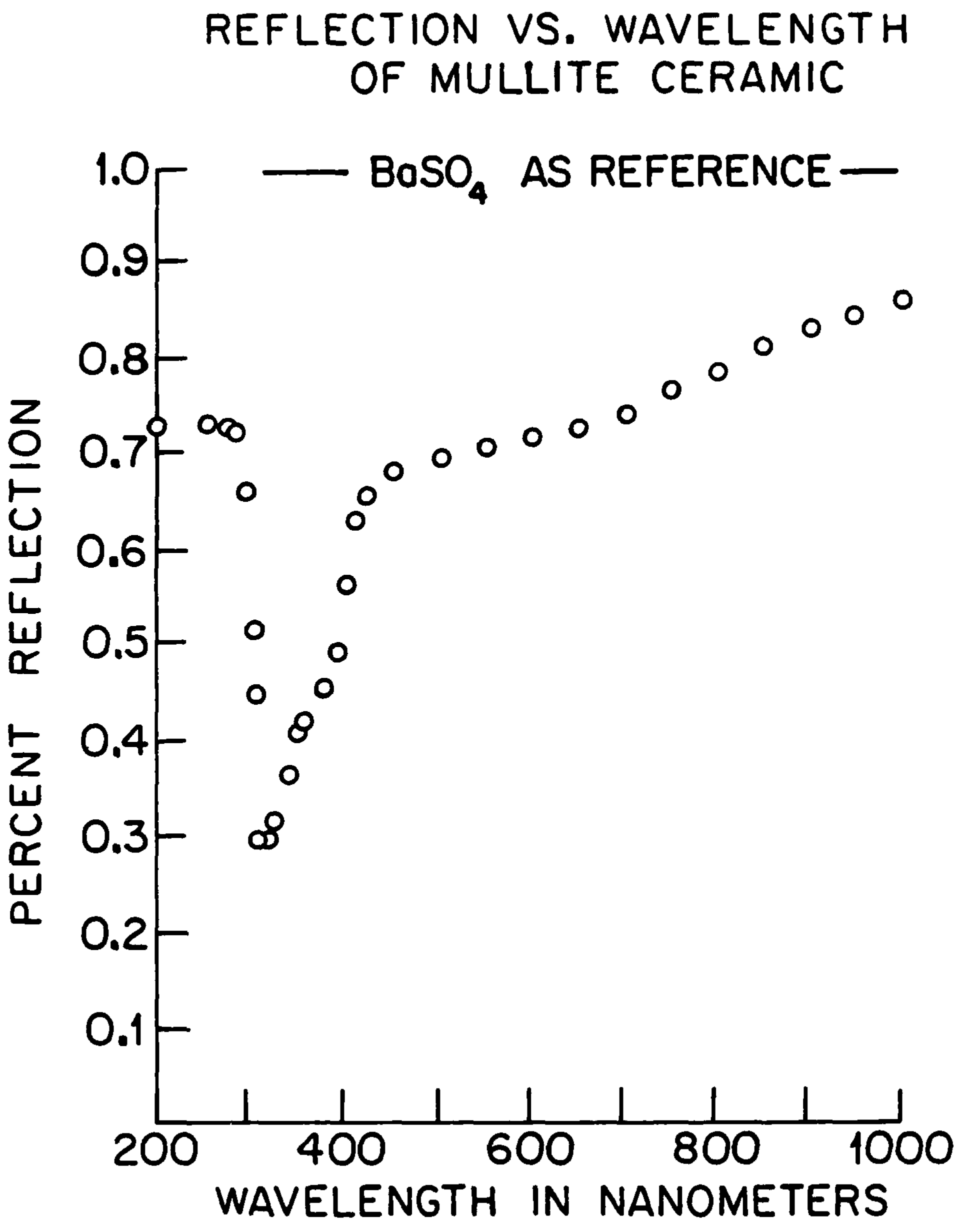
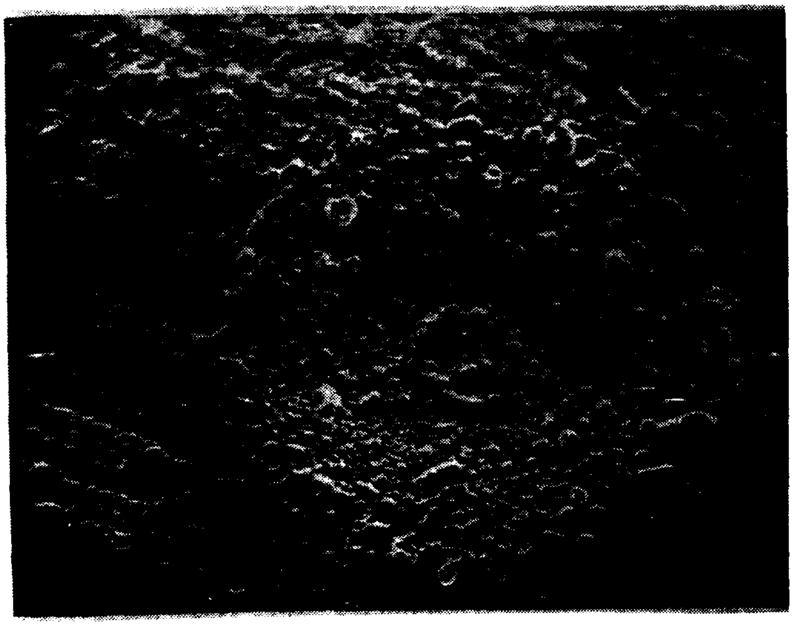


Figure 7. Reflectivity versus wavelength of mullite ceramic. Note the strong drop in the region near 330 nm suggesting a strong increase in absorption.



180 μm

SEM of Laser Irradiated Site on Mullite

Figure 8. Scanning electron micrograph of laser irradiated site on mullite. The 1.06 μm Nd:glass laser was used.

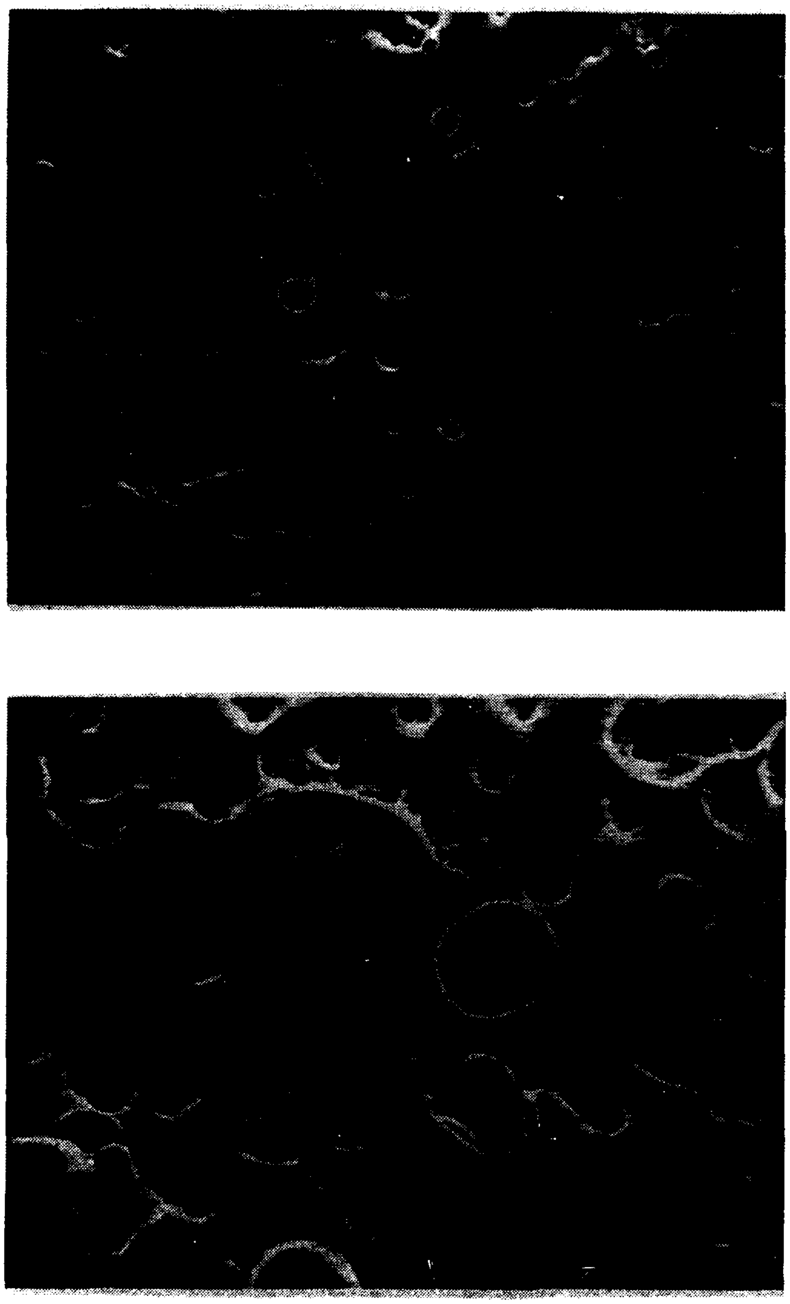


Figure 9. Scanning electron micrographs of laser irradiated mullite showing the extensive melting in the irradiated sites.

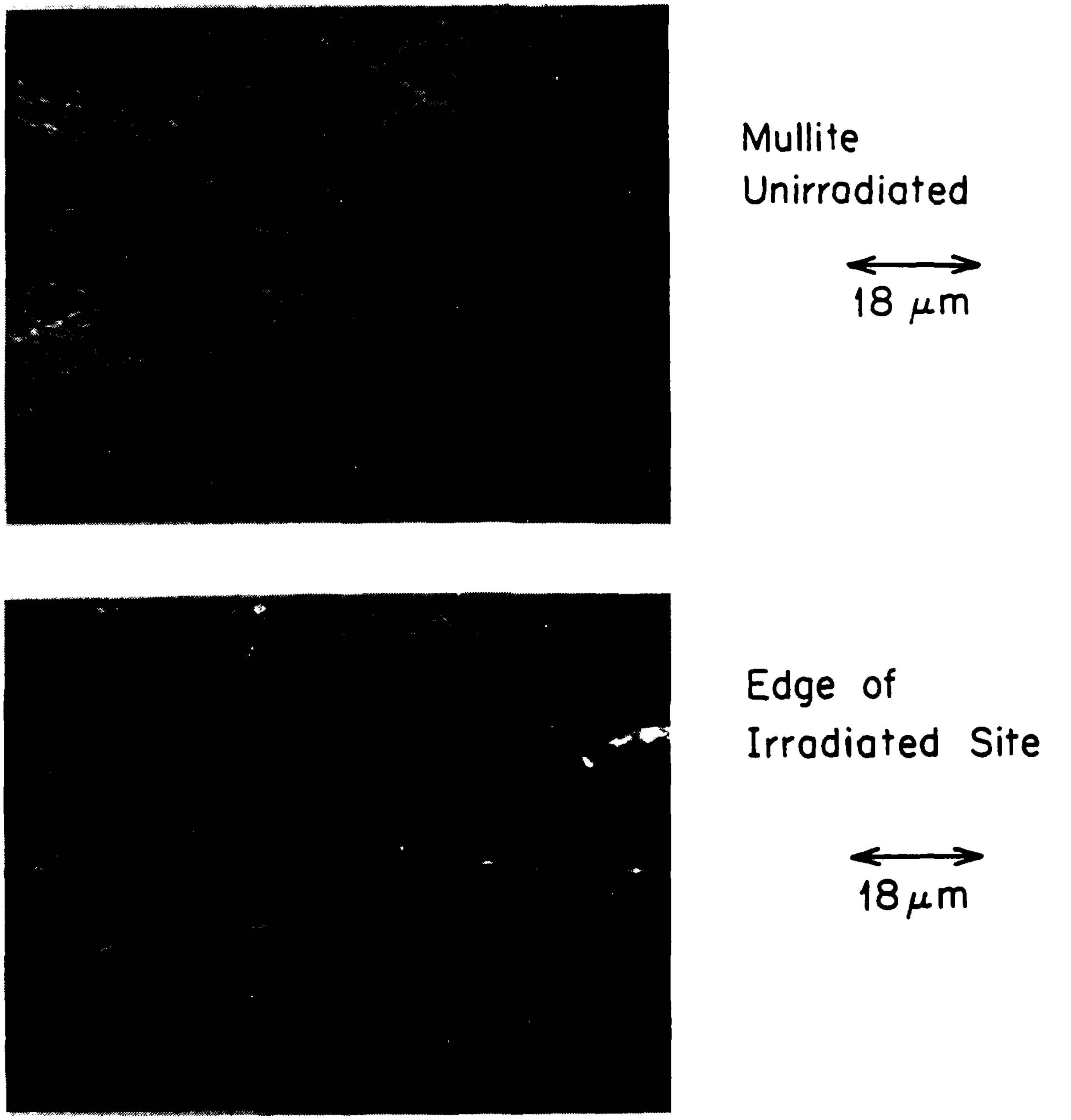


Figure 10. Scanning electron micrographs of laser irradiated mullite showing the difference between irradiated and unirradiated material.

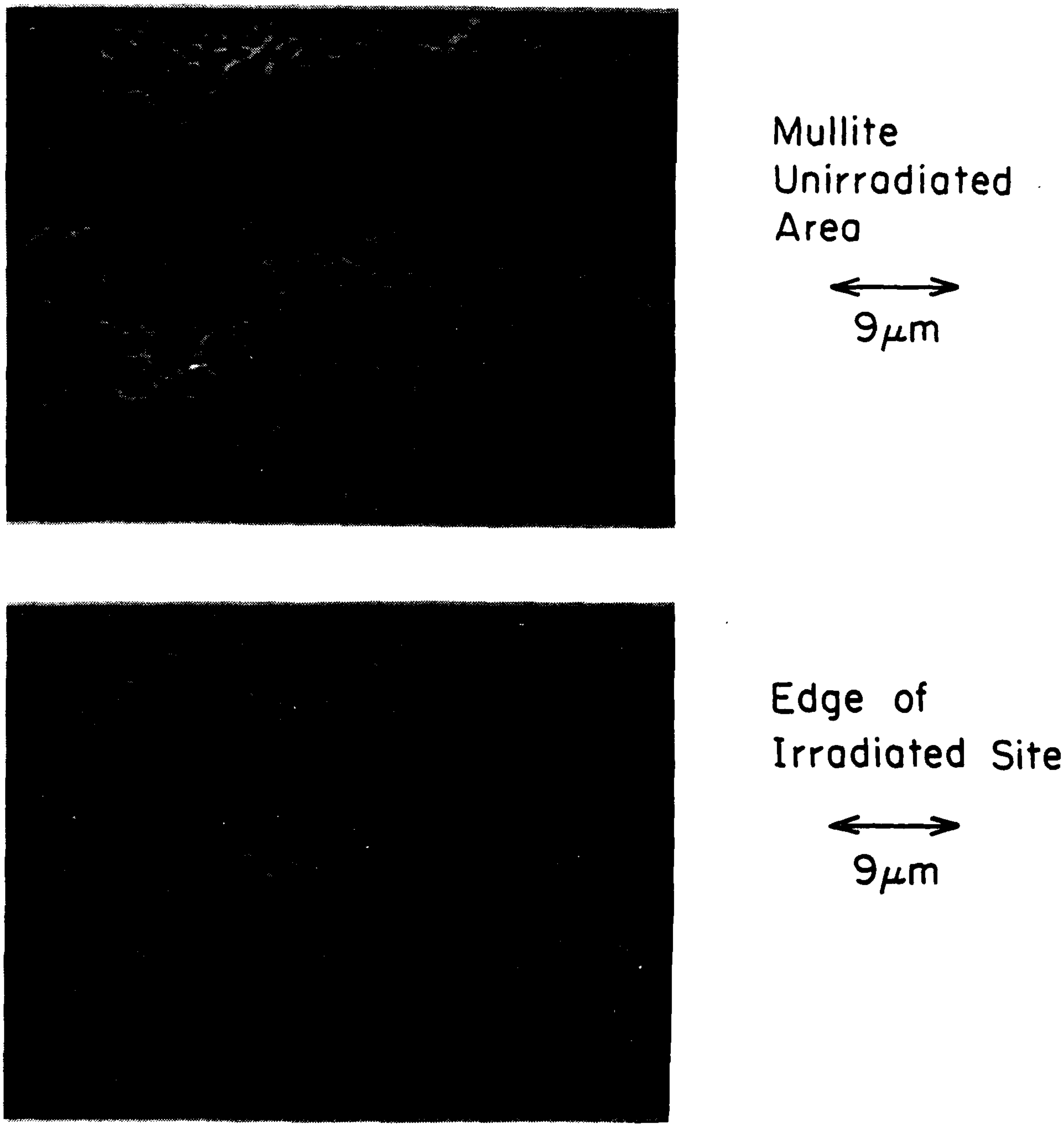


Figure 11. Scanning electron micrographs of laser irradiated mullite showing more detail of the irradiated material.

Figure 12. Scanning electron micrographs of laser irradiated mullite showing the spherical beads formed within some of the irradiated sites.

reveal them.

2.6 The Role of SEWs in Laser Interactions with Plastic. Acrylic plastic which has the transmission spectrum shown in Figure 13 was studied. This material is highly transparent at 1.06 um and so it was not possible to find irradiation conditions which allowed surface interactions only. When surface damage was produced, it was in the form of large fractures and macroscopic material removal. Other irradiation conditions which produced no such surface damage produced no detectable other type of surface disruption. However, these conditions did produce internal damages and careful examination of these revealed that many had grating like structures. Figures 14 to 18 show several of these sites and the irradiation conditions used to create them.

2.6.1 Note that the internal grating like structures are not always oriented as the simple SEW theory says they should be with respect to the light polarization. They do not have the predicted spacing. The internal sites are often at different angles of incidence with respect to the incoming laser beam and this can account for some of the discrepancies, but not all of them. Further, the internal grating structures are thought to be formed as follows: in some early pulse a crack is formed and some later pulse interacts with the surfaces of the crack to form the gratinglike structure. It also should be noted that internal gratinglike structures are not easily found when the number of pulses used to irradiate the sample is small. Whether this is because there are fewer

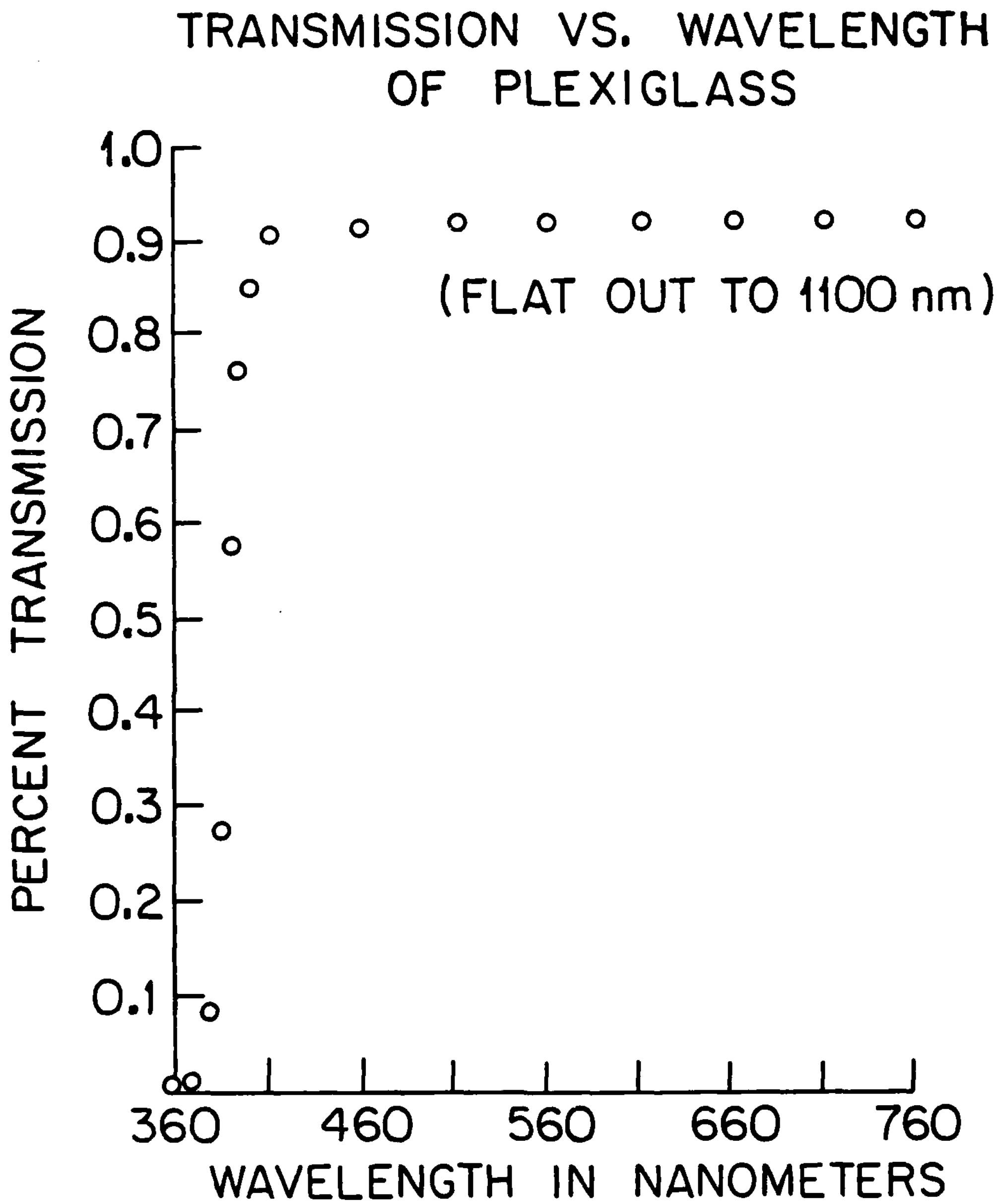


Figure 13. Transmission versus wavelength for the acrylic plastic.

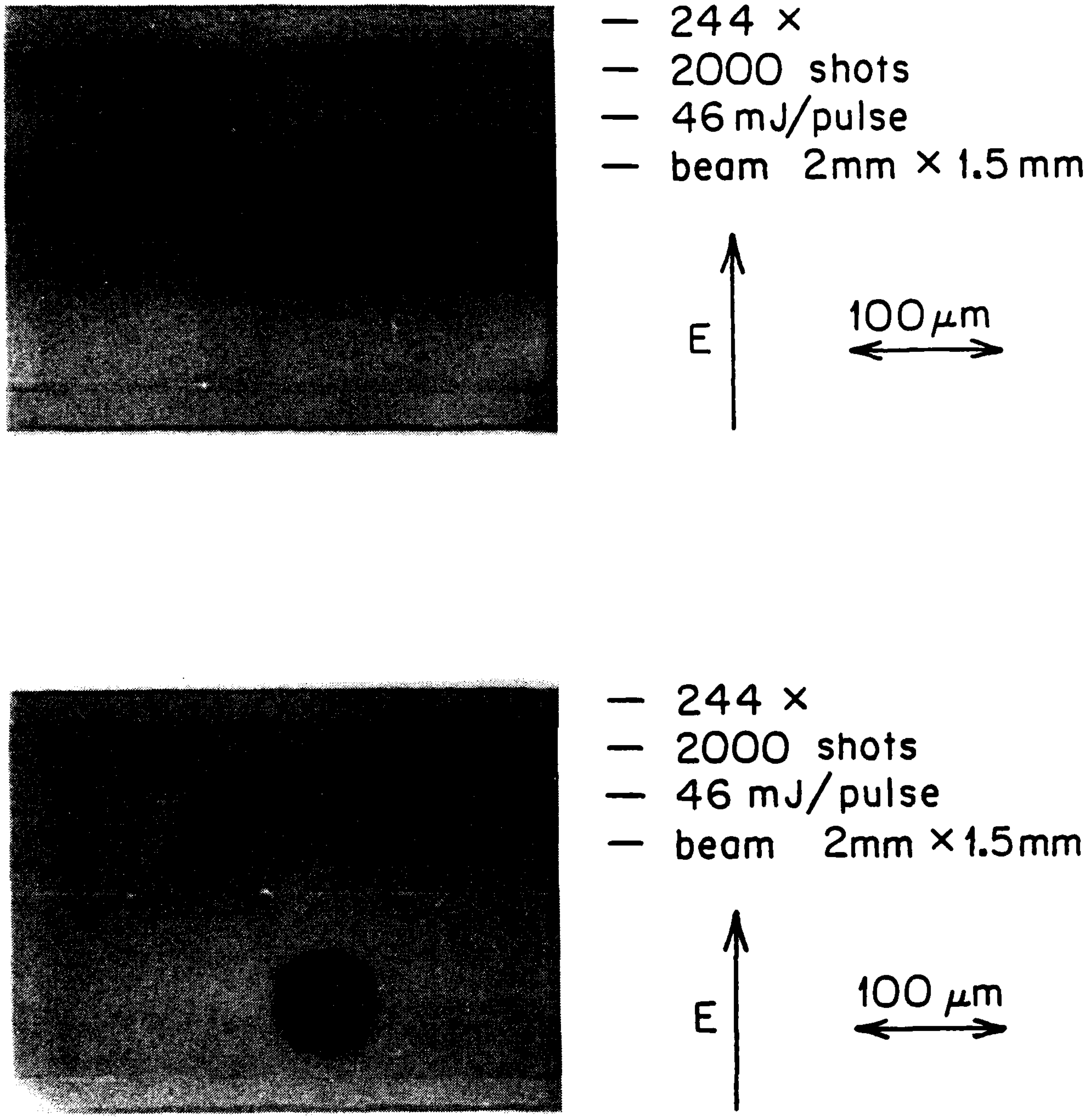


Figure 14. Optical micrographs of sites of internal grating-like structures in acrylic plastic. The two shown are in close proximity to one another but at different depths within the sample. Here they show similar orientations but different ripple spacing. The irradiation was performed with an Nd:YAG laser gently focused beyond the sample. The laser was operated at 10 Hz.

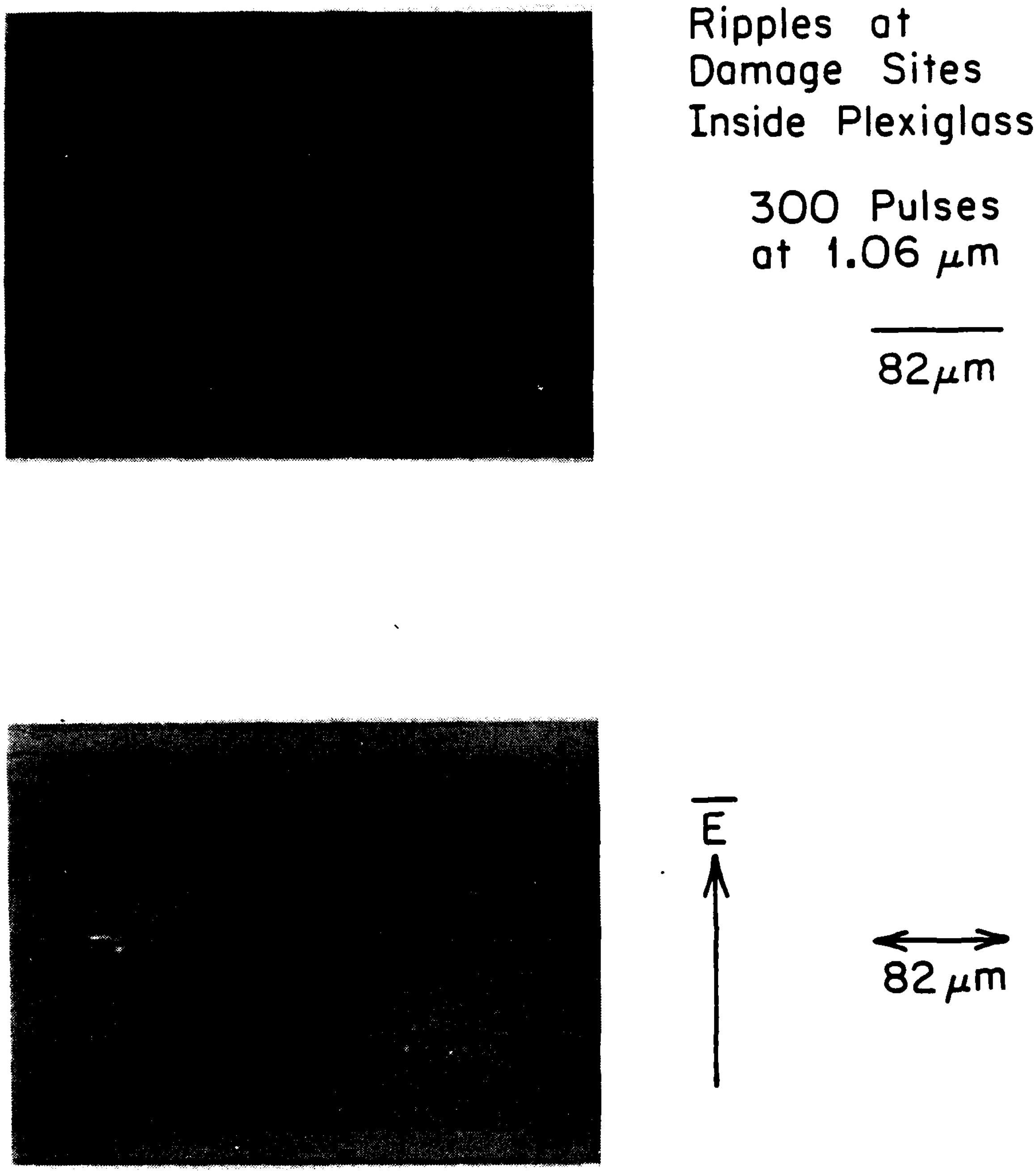
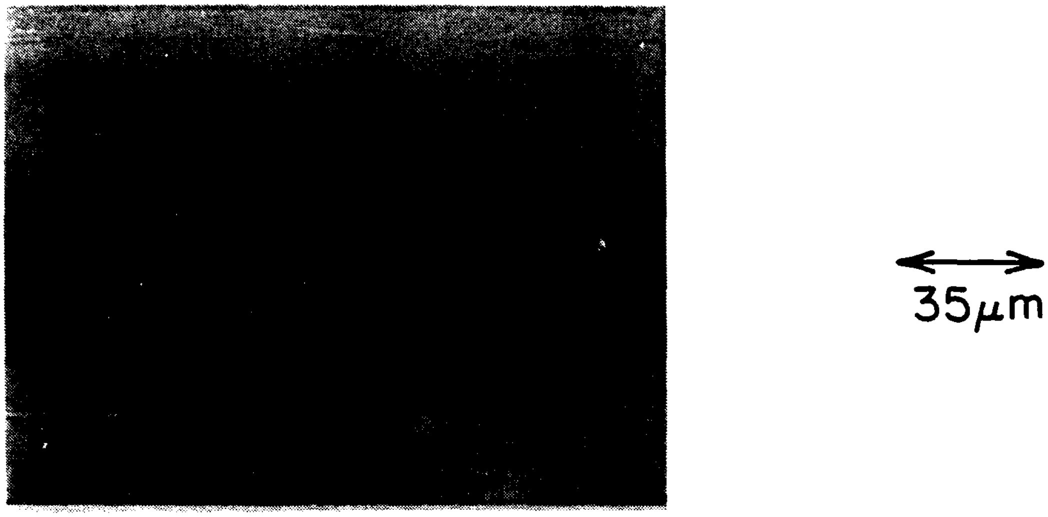


Figure 15. Optical micrographs of sites of internal grating-like structures in acrylic plastic. Showing differently oriented and spaced ripples in the internal grating-like structures.



(Cont'd)
Figure 15. Optical micrographs of sites of internal grating-like structures in acrylic plastic. Showing differently oriented and spaced ripples in the internal grating-like structures.

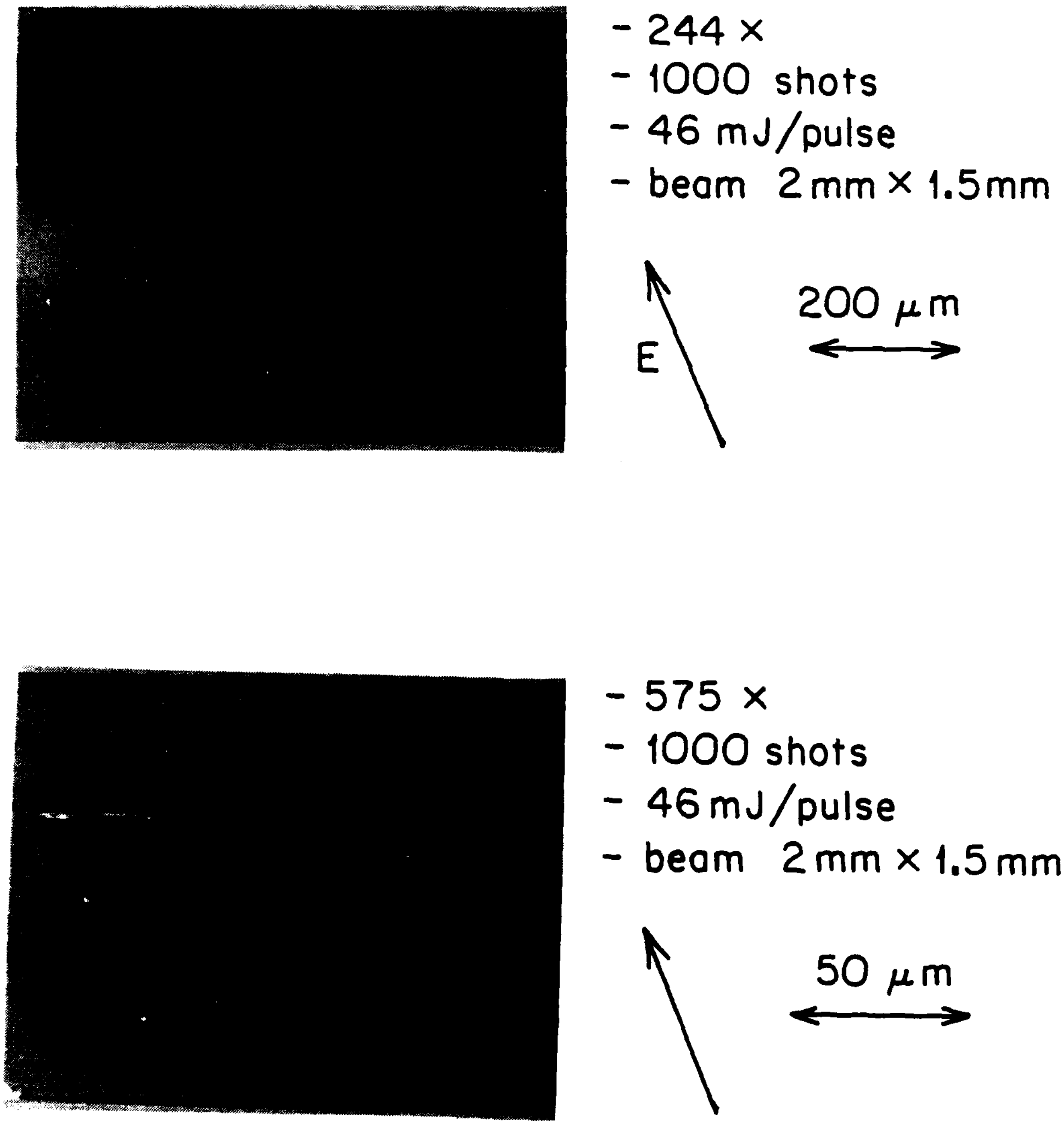


Figure 16. Optical micrographs of sites of internal gratinglike structures in acrylic plastic. This is a multiple crack with several grating like structures and when viewed in this fashion some of them are superposed to form Moire patterns.

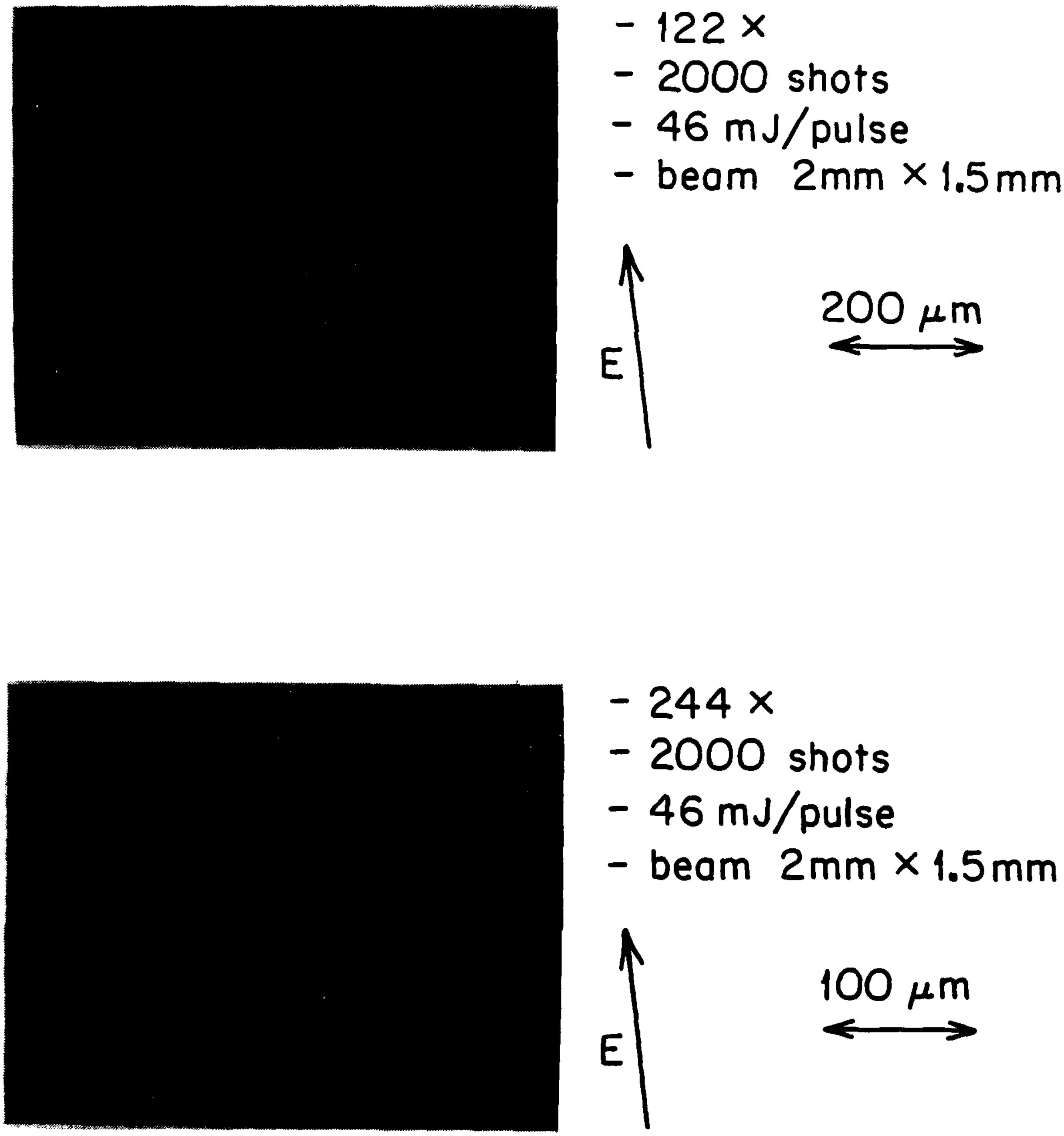


Figure 17. Optical micrographs of sites of internal gratinglike structures in acrylic plastic. These are shown to indicate the variety of spacings and orientations to be found in internal grating-like structures.

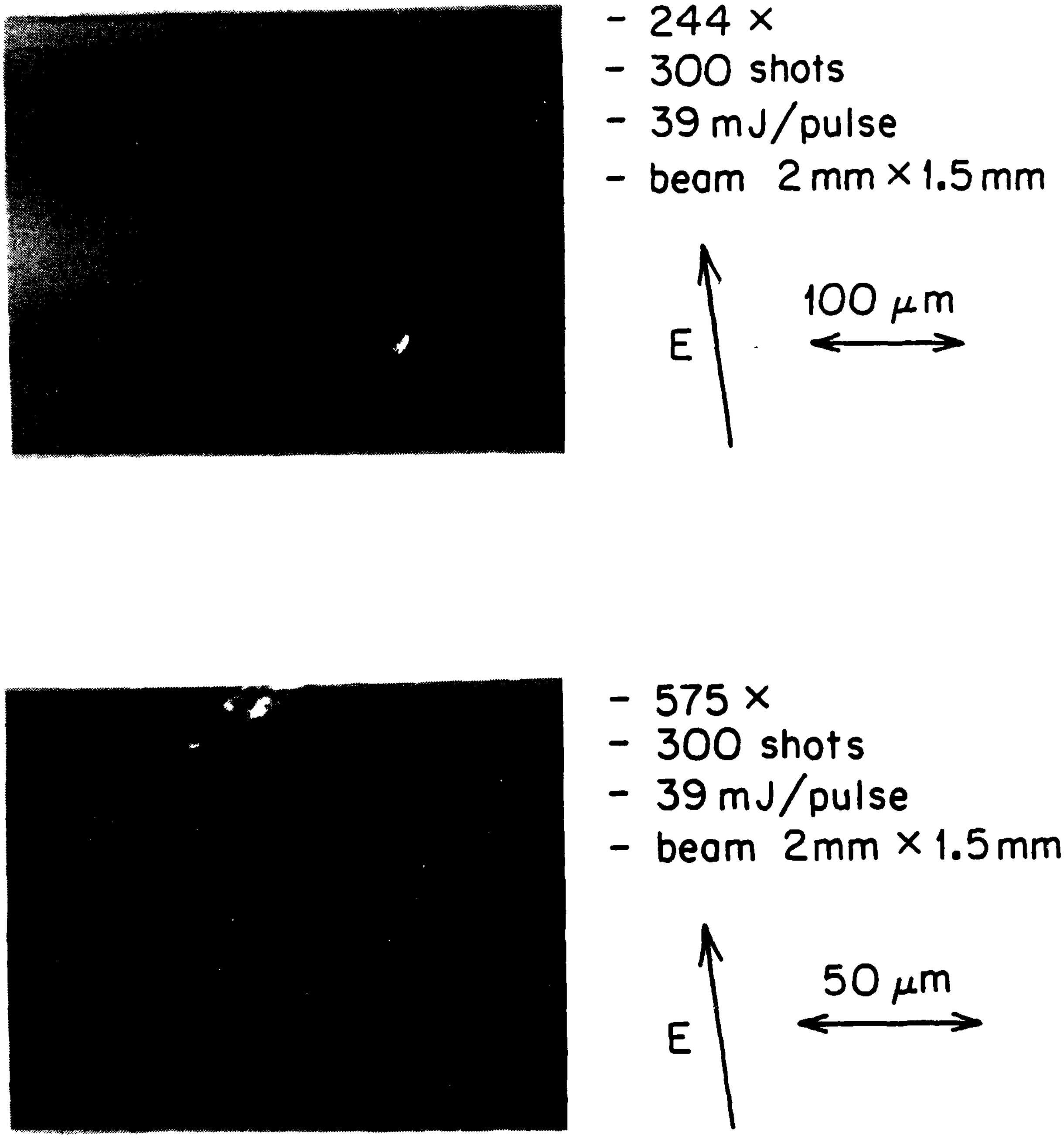


Figure 18. Optical micrographs of sites of internal gratinglike structures in acrylic plastic. These are shown to indicate the variety of spacings and orientations to be found in internal grating-like structures.

damage sites or whether there are proportionally fewer sites with gratinglike structures must be determined in future work. The simple SEW theory does not consider a case where the surface is the interface between two sides of an internal crack and clearly a more detailed analysis is called for. This may include a study of the literature concerning waveguide propagation as it may be possible to treat the internal crack as a waveguide.

2.6.2 Analysis of the electromagnetic theory of gratings may help in understanding some of the properties of internal gratinglike structures. In this theory the ripple spacing in such structures is explained and cases are described which for transverse electric (TE) incidence give spacings comparable to those observed. Again, the theory will have to be modified to account for the presence of both surfaces.

2.6.3 Soviet researchers have reported gratinglike structures at internal cracks in plastic which are composed of lines of droplets (Ref. 2). These were produced by long duration (millisecond), several joule Nd:glass laser pulses. A model is proposed which is related to waveguide propagation of waves generated by scattering on the surfaces of the cracks. This concept will be explored to see if it is suitable to explain the present results obtained with multiple pulses of nanosecond duration.

REFERENCES

1. Schwirzke, F., "Laser Induced Unipolar Arcing", in Laser Interaction and Related Plasma Phenomena, Vol. 6, eds. H. Hora and G. H. Miley (Plenum Publishing, 1984).

2. Kondrashov, V., N. F. Pilipetskii, S. Yu. Savanin and V. V. Shukonov, Sov. Tech. Phys. lett. 11, 61 (1985).