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# Effect of Electron Bombardment Heating on Surfaces of Tungsten

H. Doering and P. Shahinian

*High Temperature Alloys Branch*
*Metallurgy Division*

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**U.S. NAVAL RESEARCH LABORATORY**
**Washington, D.C.**

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CONTENTS


| | |
|---|---|
| Abstract | ii |
| Problem Status | ii |
| Authorization | ii |
| INTRODUCTION | 1 |
| EXPERIMENTAL PROCEDURE | 2 |
| Equipment | 2 |
| Materials | 3 |
| Experiments | 3 |
| RESULTS AND DISCUSSION | 4 |
| Forms of Damage | 4 |
| Correlation of Surface Temperature and Damage | 12 |
| Cyclic Heating in the Absence of Direct Bombardment | 12 |
| Dependence of Damage on Temperature and the Magnitude of the Thermal Pulse | 12 |
| SUMMARY | 14 |
| ACKNOWLEDGMENTS | 14 |
| REFERENCES | 15 |


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## ABSTRACT

Heating to very high temperatures by electron bombardment often roughens (or damages) metal surfaces. This damage to grain boundaries and grain surfaces is examined in electropolished sheet and foil specimens of tungsten. The effects of heating by stationary and oscillating 10-kv beams are compared with the effects produced by thermal radiation. At moderate temperatures, stationary beams induce grain boundary grooving as does thermal radiation, while oscillating beams produce ripples in the surface. At high temperatures, stationary beams and thermal radiation produce pits, while oscillating beams produce cracks, and tilted and dislodged grains. The more severe effects produced by oscillating beams are shown to be associated with thermal cycling.


## PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

## AUTHORIZATION

NRL Problem M01-09
Project RR 007-01-46-5407


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# EFFECT OF ELECTRON BOMBARDMENT HEATING ON SURFACES OF TUNGSTEN

## INTRODUCTION

Recent developments in electron beam technology have provided an efficient means of heating for annealing and mechanical property evaluation of refractory metals up to the very high temperatures near their melting points. However, it has been observed that at these high temperatures and for long periods of time, bombardment often produces changes in the surface of the specimen taking the form of a general roughening, Fig. 1, herein referred to as damage (1). The deterioration of anodes in vacuum tubes has also been observed and attributed to impulses of heat flow due to electron bombardment (2). Electrons bombarding the surface of materials penetrate and dissipate their kinetic energy within a very shallow layer. It can be calculated (3) that a 100-kv beam bombarding tungsten dissipates its energy in a layer $8 \times 10^{-3}$ mm in depth, while a 10-kv beam dissipates its energy in a layer only $10^{-4}$ mm in depth. Heat generated in such a thin layer implies the possibility of rapid heating and the existence of a steep temperature gradient.

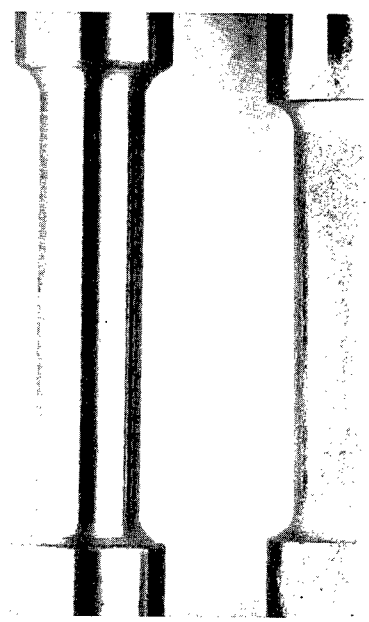

Fig. 1 - Typical damage to surface of tungsten specimen by electron bombardment. (Left: unexposed; right: damaged at 60 cps and 2000° C.) 2.7X. Reduction in printing approximately 20%.

It was the purpose of this investigation to examine the morphology and causes of the damage to electron bombarded surfaces as well as to determine operating conditions under which it occurs. The effects of heating tungsten in the range of 1600° to 3000° C by thermal radiation and by electron bombardment with both stationary and oscillating beams were compared. Grain surfaces and grain boundaries in both coarse and fine grain sheet specimens as well as foils were separately examined to determine the effects of each mode of heating.

## EXPERIMENTAL PROCEDURE

### Equipment

In this study specimens to be examined for the effects of bombardment were heated by 10-kv electron beams generated in two 3-kw self-accelerating guns. The guns are positioned 180 degrees apart, as shown in Fig. 2, so that both sides of a specimen can be heated simultaneously. The beams, which may be focused to spot diameters of 0.5 to 2.0 cm, can either be held stationary or be caused to oscillate sinusoidally and sweep over the surface of the specimen at frequencies from 20 to 3000 cycles per second. It should be mentioned that the beams are not uniform in density and the accelerating high voltage contains a 4 percent ripple. Also, the filaments and other beam control circuits are powered by alternating currents. The total power of the beams and, hence, the temperature of the specimen is controlled by the adjustment of emission current. The guns and the specimen are contained in a water-cooled chamber evacuated to an operating pressure of $8 \times 10^{-6}$ torr.

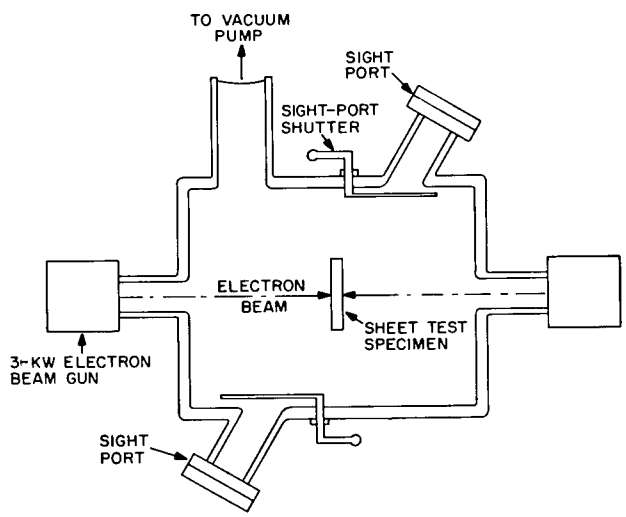


Fig. 2 - Schematic plan view of electron beam furnace

The specimen could be heated not only by direct bombardment of the surface but also by thermal radiation using two susceptors adjacent to the specimen. In addition, when only one side of a specimen was bombarded, thermal radiation heating was simulated on the opposite side. It is not likely that electrons bombarding one surface penetrate the entire thickness of the specimen and dissipate energy in the opposite surface or otherwise disturb it. Even with the foil such penetration is unlikely, since its thickness of 0.13 mm is far greater than the calculated penetration depth of $10^{-4}$ mm. Since the surface of the side opposite the beam displays the same characteristics as surfaces heated to the same temperature between susceptors, these two means of heating will be considered equivalent.

The procedure for temperature measurement employs the standard technique of drilling a blackbody hole (depth to radius ratio of 16) into a dummy specimen whose surface has the same geometry and finish as that of a test specimen. After correcting for sight-port glass attenuation, an empirical correlation between surface brightness and blackbody temperature was established with a calibrated optical pyrometer (4). To minimize the errors introduced from metallic vapor deposits, shutters covering the sight port are opened only when making measurements.

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## Materials

Three heats of nominally 99.95 percent tungsten were used in the study; two heats (WG and WH) were of 1/16-in. sheet and the other heat (WF) of 0.005-in.-thick foil. All heats were manufactured by standard powder metallurgical techniques and their spectrochemical analyses showed their major impurities to be Fe, Al, Mo, and Si. Specimens for examination of both sheet and foil were cut into tabs 2-1/8 in. by 3/8 in. Each sheet specimen was recrystallized for 90 minutes at 2300°C to obtain a stable grain size so that grain boundary migration would not occur during damage experiments. Only the foils were not so treated, since they become brittle on recrystallization and more difficult to handle without breakage.

The two heats of sheet tungsten recrystallized to widely different grain sizes. One heat (WG) characteristically recrystallized to an unusually coarse grain size of 1 cm in diameter, which facilitated the separate examination of damage to grain boundaries and grain surfaces. The other heat (WH), however, recrystallized to a fine grain size of 1 to 2 mm in diameter and permitted examination of damage in more commonly found polycrystalline materials.

A smooth surface was obtained by electropolishing all specimens in a 2 percent sodium hydroxide solution at 1 ampere per $cm^2$ current density. Prior to electropolishing, however, the sheet specimens required mechanical polishing to 3/0 paper.

## Experiments

In order to better understand the nature and causes of damage produced by electron bombardment, the following experiments were performed. First, damage in grain boundaries and on grain surfaces was systematically observed as it developed under stationary and oscillating beams at various temperatures. These effects were compared to changes manifested by thermal radiation heating. Second, by comparing the depths of grain boundary grooves, the temperature difference between the side bombarded by a stationary beam and the side opposite was investigated in order to determine if any unusual temperatures were present in the surface. Third, an attempt was made to determine if thermal cycling was related to the type of damage produced by oscillating beams. Since foils have a lower thermal inertia than do the sheet specimens, it was possible to induce a rapid cyclic change of temperature on the side of the foil opposite a beam sweeping at low frequency. Thus cyclic thermal radiation heating could be effected in the absence of bombardment.

A fourth experiment was performed to investigate the effect of temperature on the extent of damage by oscillating beams when the magnitude of each thermal pulse, as the beam passes a point on the specimen, is held constant. Also, the effect of the magnitude of thermal pulse at equal temperatures was examined.

An expression was developed to calculate this magnitude, $\Delta T$, in terms of the sweep frequency, beam power, beam diameter, and sweep amplitude. By inspection of the diagram provided by Vibrans (3), it may be seen that for the range of dwell times used here the relationship

$$\Delta T = C P (\Delta t)^{1/2} \tag{1}$$

can be assumed applicable. The beam power density, $P$, is given in $kw/cm^2$ and the dwell time, $\Delta t$, is defined as the time, in seconds, taken by the beam to pass over a given point of the specimen. By selecting applicable values of $\Delta T$ and $\Delta t$ for tungsten from the diagram, the constant, $C$, for a 1 $kw/cm^2$ beam power density was evaluated to be

$$447.2 \text{ deg-cm}^2/(\text{sec})^{1/2}\text{-kw}.$$

Since the beam was oscillated sinusoidally according to $A \cos(2\pi\nu t)$, the relationship

$$\Delta t = \frac{1}{2\pi\nu} \left| \cos^{-1}\left(\frac{x - \frac{L}{2}}{A}\right) - \cos^{-1}\left(\frac{x + \frac{L}{2}}{A}\right) \right| \tag{2}$$

may be derived where $\nu$(cps) is the sweep frequency, $x$ (cm) is the distance along the sweep path measured from its midpoint, $A$ (cm) is the half amplitude of sweep as measured from beam centers, and $L$ (cm) is the diameter of the beam. This relationship holds for

$$0 \leq |x| < \left| A - \frac{L}{2} \right|$$

where the surface is bombarded twice per cycle. Points at and beyond $(A - L/2)$ are exposed to the beam once per cycle during the movement of the beam to the end of the sweep and return, so that for

$$\left| A - \frac{L}{2} \right| \leq |x| \leq \left| A + \frac{L}{2} \right| ,$$

$$\Delta t = \frac{1}{\pi\nu} \left| \cos^{-1}\left(\frac{x - \frac{L}{2}}{A}\right) \right| . \tag{3}$$

Substituting Eq. (2) into Eq. (1) yields an expression for the thermal pulse magnitude at any point of the sweep. Thus,

$$\Delta T = \frac{447.2\ P}{\sqrt{2\pi\nu}} \left| \cos^{-1}\left(\frac{x - \frac{L}{2}}{A}\right) - \cos^{-1}\left(\frac{x + \frac{L}{2}}{A}\right) \right|^{1/2} \tag{4}$$

for

$$0 \leq |x| < \left| A - \frac{L}{2} \right|$$

and by substituting Eq. (3) into Eq. (1) a similar expression for $\Delta T$ at the points near the ends of the sweep may be obtained. It turns out that $\Delta T$ attains a maximum value at $A - L/2$; this maximum value may be several times greater than that at the center of the sweep.

A variety of combinations of beam power densities from 2 to 14 kw/cm$^2$ and sweep frequencies from 30 to 1470 cps were so selected that the calculated amplitude of each thermal pulse was held constant even though the mean temperature varied from 1520° to 2540° C.

## RESULTS AND DISCUSSION

### Forms of Damage

The effect of bombardment on tungsten surfaces takes several forms. These include rippling and pitting of grain surfaces, grain tilting, uneven grain boundary grooving, and cracking. Figure 3 shows, in a general way, how these forms of damage progressed with increasing beam power and temperature. Each mode of heating produced characteristic changes in the surface. The surfaces of bombarded specimens were examined by light, interference, and electron microscopy as well as x-ray diffraction.

Heating by thermal radiation produced two different effects. At 1400° C for 150 min, grooving of the type similar to that shown in the interference micrograph in Fig. 4 was apparent in both coarse grain and fine grain sheet material as well as foils. The grooving here should be noted for its evenness, a condition which persists to very high temperatures. At 3300°C, which is near the melting point of tungsten, the surfaces of grains displayed pits, or facets, as shown in Figs. 5 and 6.

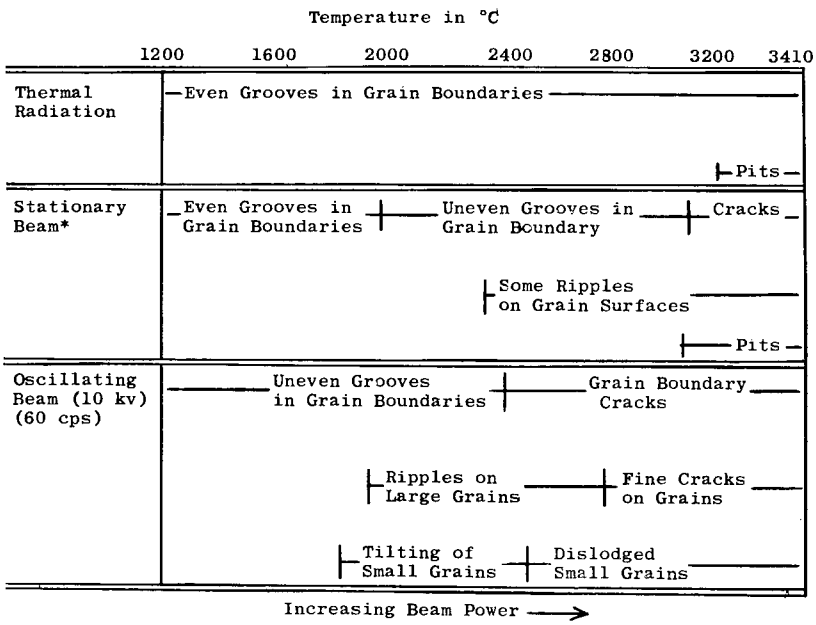


Fig. 3 - Approximate temperature ranges in which various surface effects are induced in tungsten by different modes of heating for 30 min. (*Stationary beam has voltage and current fluctuations.)

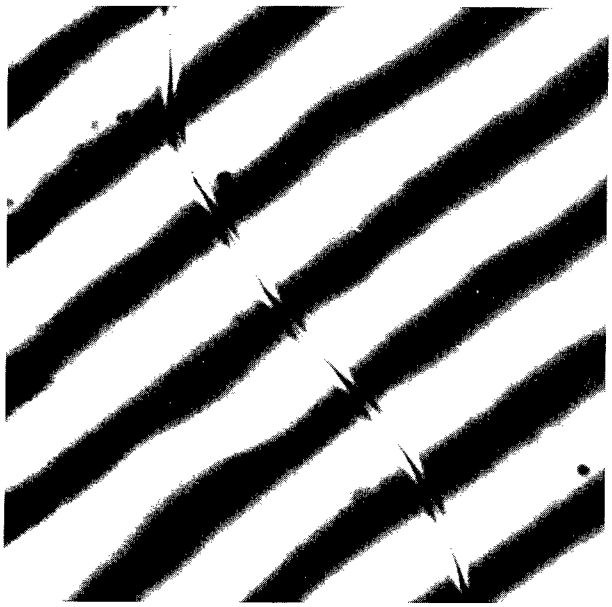

Fig. 4 - Interference micrograph of an even grain boundary groove after heating to 2600° C for 90 min by thermal radiation. 650X. Reduction in printing approximately 20%.

Fig. 5 - Micrograph of pitted surface after heating to 3300 °C by thermal radiation for 30 min. 100X. Reduction in printing approximately 20%.

Fig. 6 - Electron micrograph of pits formed on tungsten surface at 3300 °C by thermal radiation for 30 min. 18,000X. Reduction in printing approximately 20%.

Stationary beams produced changes in the surfaces of grains and grain boundaries similar in most respects to those produced by thermal radiation both a low and high temperature. At high temperatures near 3000°C, pitting on grain surfaces under the stationary beam had a form similar to the pitting produced by thermal radiation, but, in addition, the presence of ripples was observed. At temperatures below 1800 °C grain boundaries grooved the same as with thermal radiation. Grooving became uneven at higher beam powers and had the appearance of a series of connected pits as evidenced in the interference micrograph of Fig. 7.

Grain boundary grooving which occurs in an even manner below 1800°C by both means of heating is a well-known phenomenon attributed to surface diffusion at high temperature (5). The pits, developed at higher temperatures only, are probably due to the evaporation or expulsion of inclusions or impurities. But this pitting, in any event, is characteristic of the material at high temperatures, since it forms with thermal radiation. However, the appearance of some rippling and uneven grain boundary grooving will be seen to be characteristic of oscillating beams.

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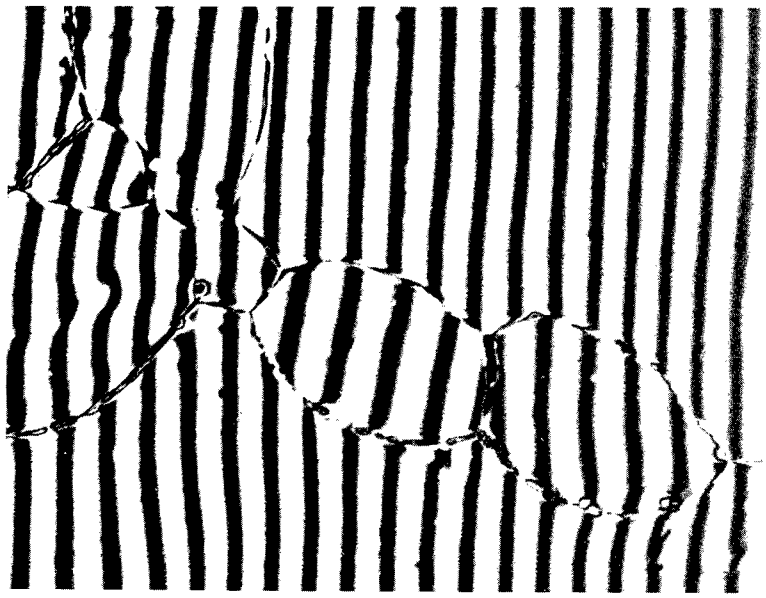
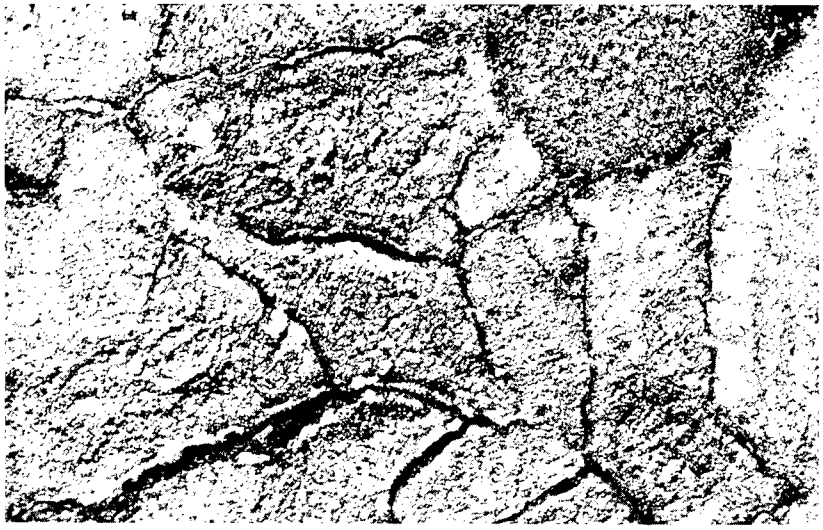


Fig. 7 - Interference micrograph of tungsten surface heated by 60 cps oscillating beam at 2000°C for 30 min. Note uneven grain boundary grooves and tilted grains. 650X. Reduction in printing approximately 20%.

The most extensive damage to surfaces was caused by low-frequency oscillating beams, as shown in Fig. 8. Damage to grain boundaries developed in the following way. At low beam powers, and hence lower temperatures (1600°C), grooving was uneven in like manner to that shown in Fig. 7. These grooves at increased beam powers gradually developed into V-shaped cracks which became as deep as 0.010 in. This behavior was similar in grain boundaries of both coarse and fine grain sheet material. It was not as extensive in the grain boundaries of foils even at high temperatures. Damage to the surfaces of large grains in sheet specimens increased with increasing beam power and temperature at low frequencies. Oscillating low-power beams at low frequencies produced ripples to the surfaces of grains, as exemplified in Fig. 9. The direction of these ripples appeared to be dependent on the crystallographic orientation of the grain although a precise correlation was not undertaken. Also, there was evidence of polygonization as seen in the breakup of spots in the Laue back-reflection pattern of Fig. 10. This breakup was induced when the rippling was caused at low beam powers and low sweep frequencies at a temperature of 1900°C.

The size of the grain itself showed an effect on the extent of damage that was observed on its surface. Shown in Fig. 9 is an example of a small grain that was unconsumed during recrystallization and subsequent grain growth in the coarse grain material (WG). A similar grain is shown in Fig. 11 taken with the interference microscope. In both figures it may be noted that the surface of the unconsumed grain is virtually undisturbed in comparison to the surface of the larger grain which surrounds it. Small grains also showed the tendency to be tilted. An example is shown by the interference micrograph in Fig. 6, where a grain is tilted 1/4 degree from its original position.

It is likely that these forms of damage produced by oscillating beams are due to thermal cycling. Thermally induced cyclic stresses on surfaces may be accommodated in two ways. When the grain is large, the stresses cause plastic deformation, as witnessed by surface ripples showing x-ray evidence of polygonization. When the grain is small, the grain boundary at sufficiently high temperatures may accommodate the strain and cause the grain to



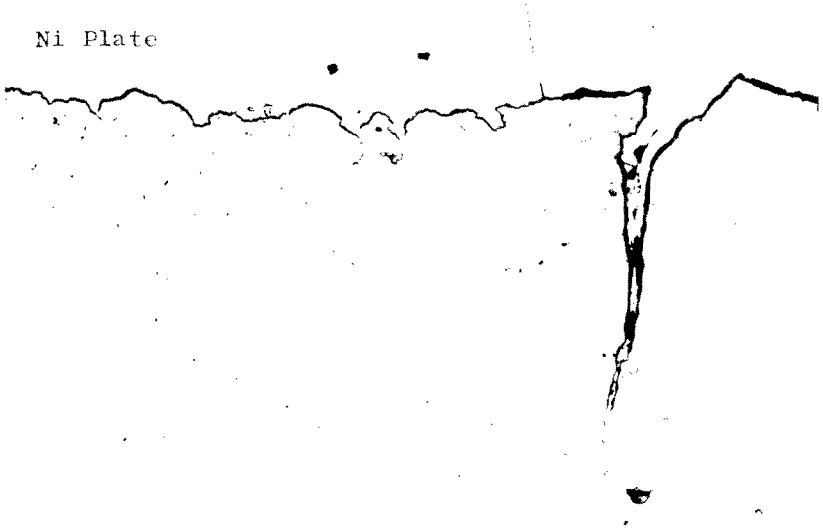



Fig. 8 - Damage to tungsten heated to 3000°C for 30 min by an oscillating beam at 60 cps: (top) specimen surface (16X); and (bottom) tapered section, 2:1. (100X.) Note deep V-shaped cracks in grain boundary and shallow cracks in grain surfaces. Reduction in printing approximately 20%.

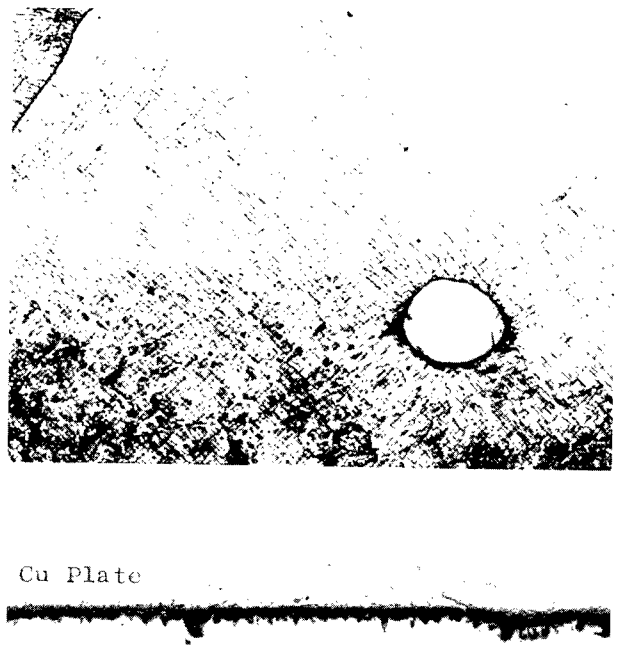



Fig. 9 - Damage to tungsten heated to 2300 °C for 60 min by a beam oscillating at 60 cps: (top) specimen surface (200X); and (bottom) tapered section, 10:1. (200X). Note in top micrograph the ripples on the large grain in contrast to the nearly undisturbed small grains. Reduction in printing approximately 20%.

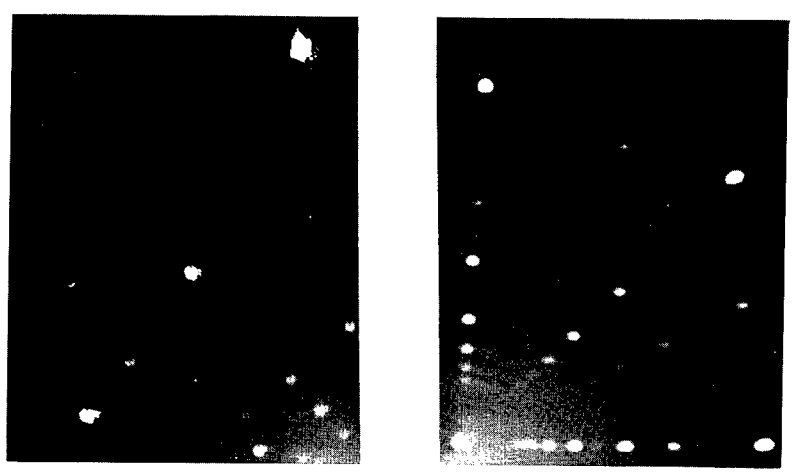


Fig. 10 - Laue back reflection patterns of rippled single grain (left) and of as-recrystallized grain (right). Note breakup of spots due to polygonization produced at 1900° C by 20 cps oscillating beams in 3 min.

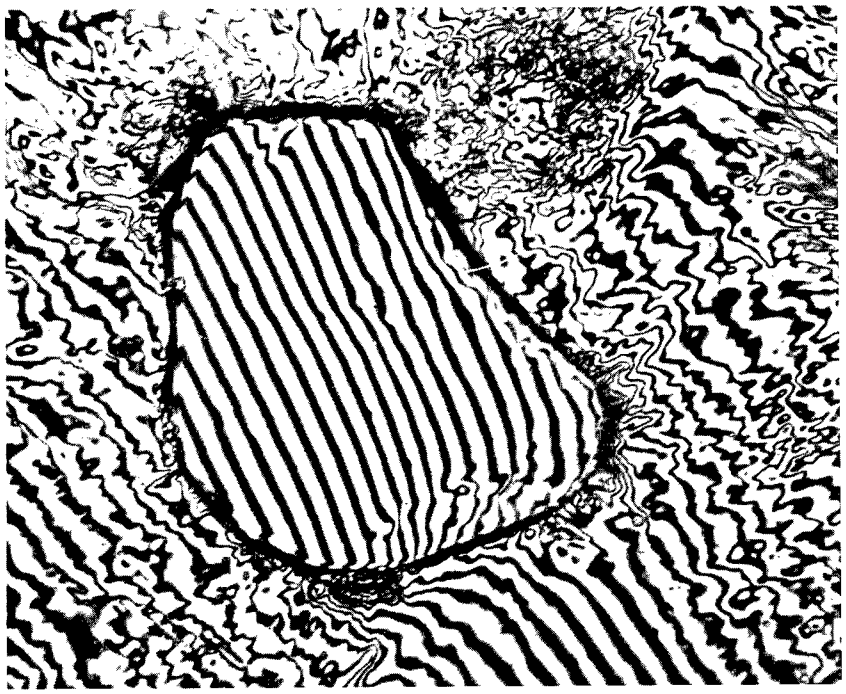


Fig. 11 - Interference micrograph of an undisturbed small grain surface within a larger grain whose surface is rippled. 800X. Reduction in printing approximately 20%.

tilt or even be dislodged without rippling. In such cases the grain boundaries do not provide the same constraint as material surrounding a point within a large grain, and ripples on the surface of the small grain are not so likely to occur. For similar reasons, heating foils by oscillating beams did not produce ripples on even its largest grain.

The formation of cracks in grain surfaces and boundaries, Fig. 8, also appears to be associated with the thermal cycling caused by oscillating beams. However, no means was available for producing thermal cycling on sheet specimens without direct electron bombardment.

Fine grain materials showed a combination of the effects produced in the coarse grain surfaces by oscillating beams, e.g., rippling, grain tilting, and uneven boundary grooving. In addition, small grains were seen to have been dislodged from the surface (Fig. 12). At temperatures very near the melting point, the metal appears to flow and produce mounds and valleys in the surface. Also at these temperatures some metal is extruded out of the surface at grain boundaries (Fig. 13).

In view of the effects produced by oscillating beams, the appearance of ripples and uneven grooves under stationary beams may be attributed to minor fluctuations in the beam itself. These fluctuations could be caused by the 4 percent ripple in the high voltage as well as alternating currents in the filament and other beam control circuits and may well induce thermal cycling similar to that induced by oscillating beams. With a steady beam it might be found that both thermal radiation and stationary beams would show very similar effects. These two means of heating however are not identical when the production of x rays, secondary emission of electrons, etc., are considered.

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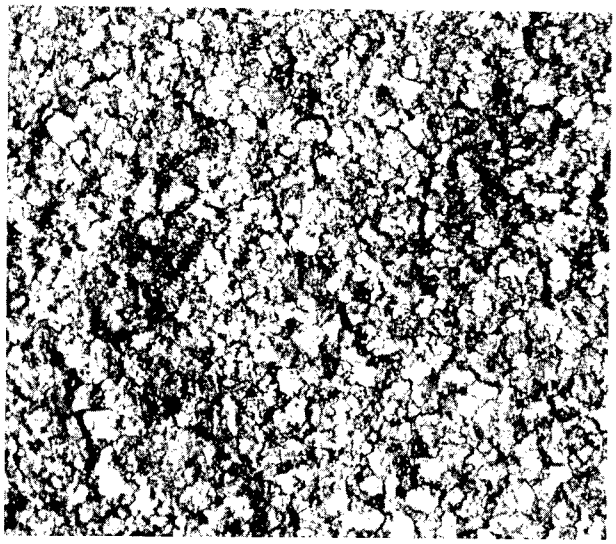

Fig. 12 - Surface of polycrystalline sample damaged by 60 cps oscillating beam at 2600°C for 30 min showing tilted and dislodged grains. 35X. Reduction in printing approximately 20%.

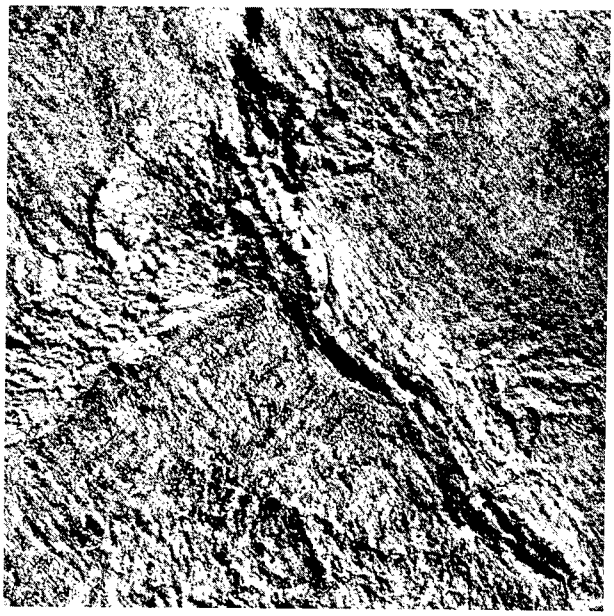

Fig. 13 - Severe damage to tungsten by 60 cps oscillating beam at 3000°C for 15 min showing metal extruded up adjacent to grain boundary. 20X. Reduction in printing approximately 20%.

## Correlation of Surface Temperature and Damage

Measurements made with the interference microscope of grain boundary groove depths provided a means to indicate the temperature of surfaces bombarded by a stationary beam. A specimen heated to a mean temperature of 1800°C for 30 min showed groove depths of 700 to 900 A in the area heated by the beam, while those on the opposite side were less. To obtain comparable groove depths on the side opposite the beam a specimen had to be heated to a mean temperature of 2000°C. Thus a temperature difference of about 200°C was established between the two surfaces. The temperature difference indicated by the optical pyrometer was 100°C. The agreement, although only approximate, suggests that no unusually high temperature forms in the surface layer where the beam dissipates its energy. Above 1800°C in 30 min groove depths could not be measured because of their unevenness.

A similar, although less precise, relationship was observed on the bombarded area of a specimen heated to 3000°C. There pitting, as shown in Figs. 5 and 6, was comparable in extent and nature to that found in the area opposite the beam of a specimen heated to 3300°C, so that a difference in the order of 300°C was established between the bombarded side and the side opposite.

## Cyclic Heating in the Absence of Direct Bombardment

The use of foils made it possible to determine the effect of thermal cycling in the absence of direct bombardment by observing the surface opposite the beam. When one side of a foil was bombarded with a beam oscillating at a low frequency (20 cps), it was possible to see a rapid cyclic change in brightness on the side opposite the beam. Thus this side of the foil was being subjected to thermal cycling while not being bombarded. Grain boundaries on this side as well as the bombarded side were uneven. On heating other foils to the same temperature between susceptors boundary grooving was even. This experiment clearly demonstrates the dependence of uneven grooving on thermal cycling. It is very likely that the ripples and cracks caused by oscillating beams are also due to thermal cycling.

## Dependence of Damage on Temperature and the Magnitude of the Thermal Pulse

It was found that the extent of damage is not only dependent on the magnitude of the thermal pulse, but on the temperature of the specimen as well. By varying the beam power density and sweep frequency (Table 1) the thermal pulse, $\Delta T$, according to the assumed relationship in Eq. (4), was held at nearly constant amplitude for the series of damage experiments at different temperatures shown in Fig. 14. The extent of roughening in specimens 5 and 6 is seen to be quite similar, although at the extreme temperatures the damage is reduced. The material is stronger at the lower temperature and can better accommodate the thermally induced stresses. At the highest frequency (specimen 7) the extent of damage is also seen to be less. The relationship describing $\Delta T$ departs most from the more exactly calculated values (3) in the case of specimen 7 as well as specimens 1 and 2, so that the actual magnitude of thermal pulse may in fact be less than that calculated for this experiment.

The dependence of damage on the magnitude of thermal pulse is shown in Fig. 15. Here two specimens were heated to the same temperature, 2500°C, but the thermal pulse was different for both, since they were damaged at sweep frequencies of 540 and 3000 cps. The difference in extent of the resulting damage yields a basis for establishing operating conditions where no damage of this type occurs. Decreasing either the beam power density or the dwell time reduces the pulse magnitude and consequently the damage. Beam power density may be decreased, still maintaining a given temperature, by broadening the beam

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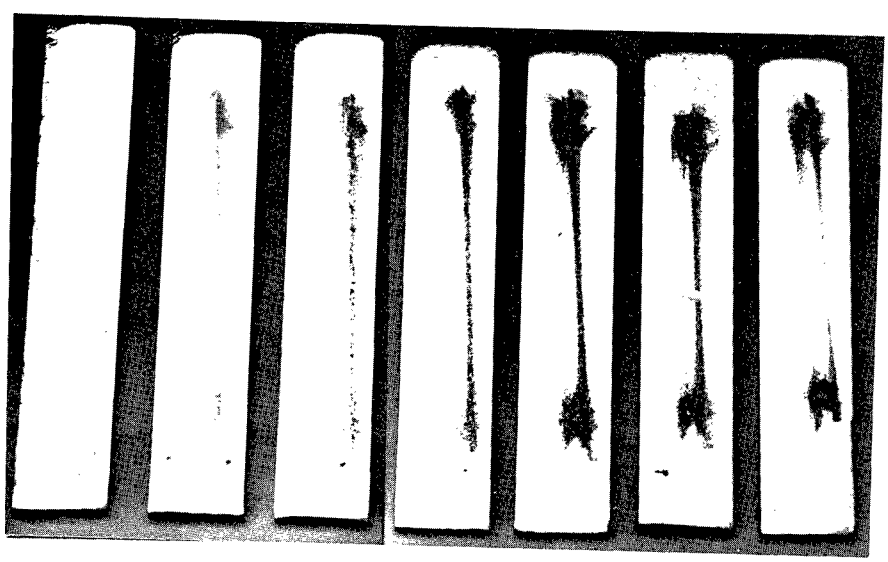
Table 1
Operating Conditions for Heating with Constant Magnitude of Thermal Pulse

| Specimen Number | Beam† Power Density ($kw/cm^2$) | Sweep Frequency ($sec^{-1}$) | Sweep Ampl. 2A (cm) | Calculated* Therm. Pulse at Midpoint (°C) | Calculated* Therm. Pulse at Ends (°C) | Mean Temp. (°C) |
|---|---|---|---|---|---|---|
| 1 | 2 | 30 | 3.8 | 33 | 79 | 1520 |
| 2 | 4 | 120 | 3.8 | 33 | 79 | 1880 |
| 3 | 6 | 270 | 3.8 | 33 | 79 | 2040 |
| 4 | 8 | 480 | 3.8 | 33 | 79 | 2220 |
| 5 | 10 | 750 | 3.8 | 33 | 79 | 2360 |
| 6 | 12 | 1080 | 3.3 | 35 | 82 | 2450 |
| 7 | 14 | 1470 | 3.3 | 35 | 82 | 2540 |

*The calculations are based on Eqs. (1) through (4). The values at the ends are calculated for the maximum dwell time at $x = A - \frac{L}{2}$.

†One beam was used with a spot 0.5 cm in diameter. All specimens of Fig. 14 were exposed for $5 \times 10^5$ sweep cycles; thus the ends were exposed to $5 \times 10^5$ pulses, and the midpoint was exposed to $10^6$ pulses.



1 2 3 4 5 6 7

Fig. 14 - Sheet specimens damaged at different temperatures but all subjected to the same thermal pulse. The extent of roughening indicates the dependence of damage on specimen temperature. The operating conditions which produced the damage are given in Table 1. 1.5X. Reduction in printing approximately 20%.

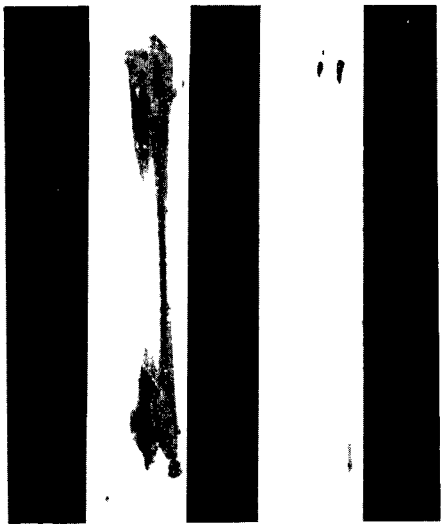


Fig. 15 - Two specimens damaged at 2500 °C for 30 min by oscillating beams at different sweep frequencies: left, 540 cps; and right, 3000 cps. The extent of roughening shows the dependence of damage on the magnitude of thermal pulse. 1.5X.

spot diameter or using several guns. The magnitude of the thermal pulse may also be reduced by increasing the sweep amplitude and frequency, thus decreasing the dwell time. To achieve a given temperature, the thicker the specimen the more power required, so that the thermal pulse is increased.

Damage associated with thermal cycling may be minimized, but thermal grooving and pitting cannot be controlled, since these effects are due to the mean temperature of the specimen alone.

## SUMMARY

The nature of the effects (or damage) that a focused 10-kv electron beam produces on surfaces of tungsten was investigated. At temperatures between 1200° and 3400 °C the change in the surface was observed as it developed on both foils and polished sheet specimens. Electron bombardment produces damage to tungsten surfaces which appeared to be associated with the temperature to which the surface was subjected and with thermal cycling.

The types of damage produced by stationary and by oscillating beams were found to be different. Stationary beams show characteristic effects of grain boundary grooving and surface pitting similar to those manifested by thermal radiation heating. Oscillating beams, on the other hand, produce damage of a different nature that has been observed to be associated with thermal cycling. As the oscillating beam sweeps past a given portion of the specimen it induces a thermal pulse in the surface. The resulting damage includes ripples on grain surfaces, uneven grain boundary grooves, cracks, and tilted and dislodged grains. The extent of these effects is dependent on temperature as well as the magnitude of this pulse.

By increasing the frequency and amplitude of sweep and lowering the beam power density, the magnitude of the thermal pulse and the damage associated with it can be minimized.

## ACKNOWLEDGMENTS

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## REFERENCES


1. "Development of an Electron Beam Heating Facility and Its Use in Mechanical Testing of Tungsten to 6000°F," ASD-TDR-63-484, Lessells and Associates, Inc., May 1963

2. Crapuchettes, P.W., "Cooling of Anodes Subjected to Long Pulses of High Peak Power," AIEE Conference Paper, Winter General Meeting, New York, Jan. 29 to Feb. 3, 1961

3. Vibrans, G.E., "Calculation of the Surface Temperature of a Solid Under Electron Bombardment," Technical Report 268, Lincoln Lab., Massachusetts Institute of Technology, Nov. 16, 1962

4. Doering, H., and Shahinian, P., "Brightness and Two-Color Pyrometry Applied to the Electron Beam Furnace," NRL Report 6062, June 1964

5. Chalmers, B., King, R., and Shuttleworth, R., "The Thermal Etching of Silver," Proc. Royal Soc. London 193A:465 (1948)