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Examination of Electron Bombardment Heating for Effects on the Tensile Properties of Tungsten

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The effects of heating with 10-kv electron beams were studied by comparing the tensile properties of tungsten heated by electron bombardment and by thermal radiation. Bombarded specimens with both undisturbed and visibly damaged surfaces were tested at both room and high temperatures. At 2200°C the ultimate tensile strength obtained when heating by thermal radiation was found to be the same as the strength obtained when heating by electron bombardment. Also, prolonged bombardment heating at 2400°C under conditions not producing any surface changes prior to testing did not influence the tensile properties when compared to heating by thermal radiation. Normal strengths were reduced by bombardment only when surfaces were visibly damaged, the reduction being greatest at room temperature and considerably less at the higher temperature. The modes of fracture and the microstructures of failed specimens were independent of the means of heating. On the basis of these results it appears that electron bombardment heating, if properly applied, can be used in conducting valid mechanical property tests at high temperatures.

INTRODUCTION

Recent developments in electron beam technology have provided an efficient means of heating materials for mechanical property tests at very high temperatures. In a previous study (1) it was shown, however, that electron bombardment heating under certain conditions may produce a general roughening or damage to the bombarded surface. This damage is attributed to the thermal cycling induced by an oscillating electron beam as it passes over a given portion of the surface.

Even if bombardment does not visibly disturb the surface, it may cause other more subtle effects that could influence mechanical properties. For example, electrons of sufficiently high energy may cause the formation or migration of point defects (2,3) and, consequently, influence plastic flow. Also, it has been shown that aluminum and copper can be hardened during irradiation by high-energy (1-Mev) electrons (4,5). Although electrons usually employed for heating are of lower energy (5 to 20 kv), their possible effect on mechanical properties should, nevertheless, be examined. The existence and magnitude of bombardment effects must be known if this means of heating is to be applied with confidence.

It was the purpose of this study to examine the suitability of electron bombardment heating for the evaluation of mechanical properties. Initially, in order to investigate the effects of bombardment during a tensile test, the strengths obtained when heating by either thermal radiation or bombardment were compared. Next, in order to determine the effect of prolonged exposure to electron beams, a comparison was made of the tensile properties of tungsten which had been heated prior to testing by thermal radiation and by bombardment under conditions that either damaged the surfaces or left them undisturbed.

EXPERIMENTAL PROCEDURE

Materials

Three heats of 1/16-in. sheet (nominally 99.95 percent) tungsten were used in this study. These heats (A, B, and C) were manufactured by standard powder metallurgical techniques, and spectrochemical analyses showed their major impurities to be Fe, Al, Mo, and Si. Sheet tensile specimens were machined with a 1.00 in. gage length, 0.500 in. width, and 0.055 in. thickness. Heat B was machined into specimens of two thicknesses,

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0.045 in. (B1) and 0.055 in. (B2). A 1-in. length of exposed shoulders was provided to permit the attachment of extensometer clamps. All of the materials were recrystallized by thermal radiation heating at 2500°C for 30 min, producing grains 0.15 to 0.30 mm in diameter.

Equipment

The test equipment consisted of an Instron tester on which is mounted an electron beam furnace. In this furnace, tensile specimens were heated by 10-kv beams generated in two, three-element, 3-kw electron guns positioned 180 degrees apart in a chamber evacuated to 10^{-5} torr, as shown in Fig. 1. The beams, impinging normally on the specimen surface, are focused to spot diameters that cover the width of the gage section and are oscillated so as to sweep the gage section longitudinally at frequencies from 20 to 3000 cps. The amplitude of beam sweep is adjusted to heat part of the shoulders of the specimen to compensate for end losses and, thus, more easily maintain temperature gradients to less than 5°C in the gage section. Heating can be accomplished not only by direct bombardment of the surface but also by thermal radiation using two susceptors adjacent to the specimen.

Temperature measurements were made by employing the standard technique of empirically correlating the brightness of a blackbody hole (true temperature) to the brightness of a (non-blackbody) surface at the same temperature, the latter surface being similar in finish and geometry to that portion of a test specimen on which measurements would be made (6). To minimize the errors introduced from metallic vapor deposits, shutters covering clean areas of the sight glass were opened only when making optical measurements. When heating by thermal radiation, the reflections from the hotter susceptors illuminated the specimen unless shielding was provided.

The optical pyrometer, because of its high accuracy, was used to determine the temperature; however, the control of temperature was accomplished by using a two-color pyrometer, which is relatively insensitive to changes in the emissivity of the surface and to the gradual deposition of metallic vapor on the sight-port glass during the test. This pyrometer also has an output that can be fed to a recorder-controller which provides a signal to adjust the grid bias in each gun, thus changing the emission current so as to maintain the temperature within ±10°C at 2200°C.

An extensometer employing a linear differential transformer was adapted to measure strain up to 3300°C. Clamps are attached to the shoulders of the specimen, and connecting rods transfer the motion to the transformer, which is protected by a water-cooled shield in a cooler part of the furnace. This arrangement is especially suitable for this type of furnace because only the specimen is heated directly by the beams and the attached components remain considerably cooler. The value of the extensometer is demonstrated in the stress-strain curves for tungsten at 2760°C (5000°F), as shown in Fig. 2. Because the total elastic strain of tungsten at this temperature is less than the 100-μin. resolution of the extensometer, the curve obtained by the extensometer shows a step from zero to the yield stress. The corresponding part of the curve obtained by crosshead movement shows, in contrast, a gradual ascent to yield stress, but this represents the tightening, alignment, and elastic deformation of linkages in the pull rod assembly and not the strain of the specimen. The range of the extensometer is 0.120 in. but the total elongation of the specimen was 0.420 in., so in order to obtain an entire stress-strain curve it was necessary to switch to cross-head movement during the test. This procedure was found to give a realistic curve because in the flat portion of the curve, where elongation takes place under a nearly constant load, the extensometer and crosshead movements correspond.

Test Procedure

The effects of electron bombardment heating on the tensile strengths of recrystallized tungsten were investigated by two sets of experiments. In the first set, tests were conducted at 2200°C using several means of heating. The ultimate strengths obtained when thermal radiation heating was used were compared to strengths obtained when bombardment heating was used, with the electron beams oscillated at 20, 60, or 3000 cps. These frequencies were chosen because, after extended periods of exposure, surface damage occurred at 20 cps but not at 3000 cps. In general surface damage can be suppressed by using sufficiently high sweep frequencies (7).

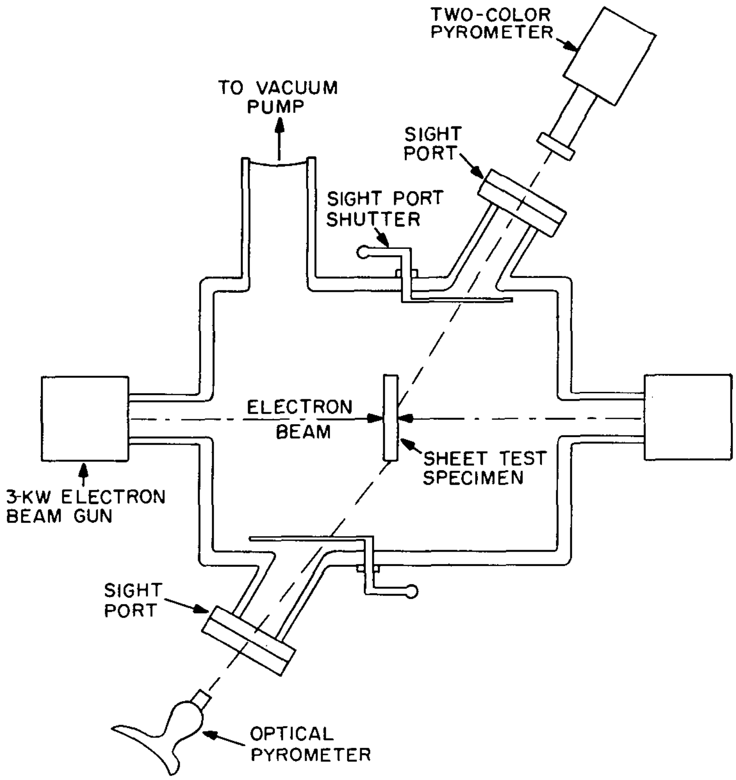

Fig. 1 — Schematic plan view of electron beam furnace

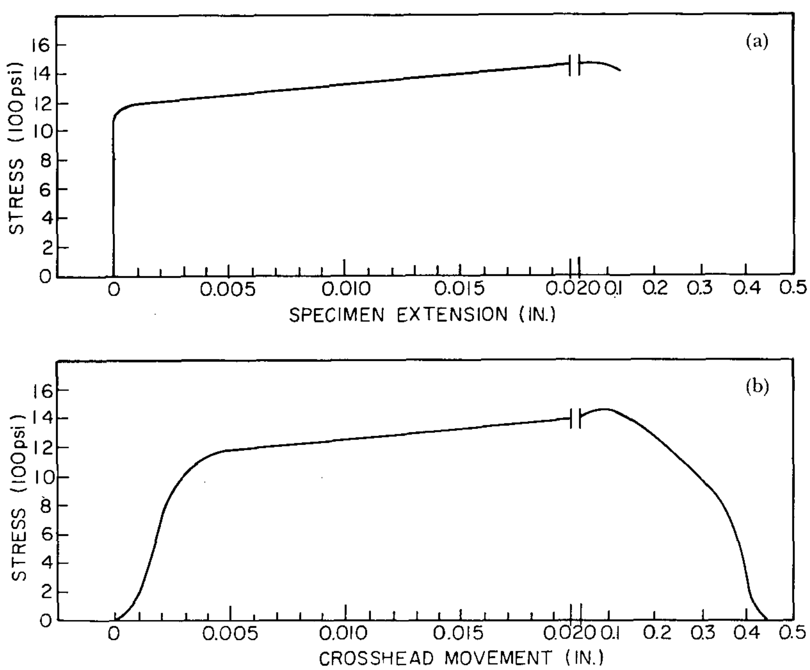

Fig. 2 — Stress-Strain curves for tungsten at 2760°C (5000°F), using a crosshead speed of 0.05 in./min, as obtained by (a) the extensometer and (b) crosshead movement. Note that the extensometer range was limited to 0.120 in.

In the second set of experiments an effort was made to magnify and, hence, more easily uncover the effects of bombardment by heating for a prolonged period with thermal radiation and with electron beams. Three groups of recrystallized specimens were heated for 30 min at 2400°C prior to testing at lower temperatures. One group was heated by thermal radiation and two others by bombardment with beams sweeping at 60 or 3000 cps. It was found that, at this temperature, a 60-cps sweep visibly damaged the surface while a 3000-cps sweep did not, as shown in Fig. 3. Tensile tests in each group were carried out at room temperature, 1200, and 2200°C. In these tests thermal radiation heating was employed to avoid any further bombardment effects. A cross-head speed of 0.05 in./min was used in all tensile tests.

Because of the high notch sensitivity of recrystallized tungsten specimens at room temperature, it was necessary to sandwich their shoulders between two pieces of cold-rolled steel with an epoxy adhesive so that fracture would occur in the gage section rather than in the fillets and pin holes.

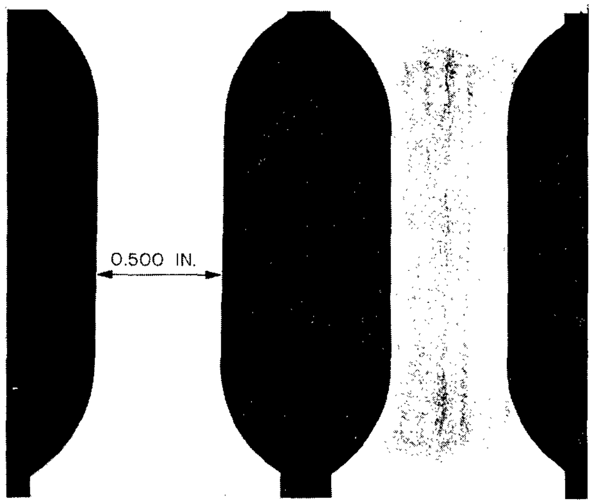

Fig. 3 — Typical damage to surface of tungsten sheet tensile specimen heated by electron bombardment at 2400°C for 30 min. Left: using 3000-cps oscillating electron beam; right: using 60-cps oscillating beam. (Original magnification 2.3X.)

RESULTS AND DISCUSSION

Tensile Properties

In the first part of the study tensile properties at 2200°C were found to be independent of the mode of heating during the test. Essentially the same ultimate tensile strengths of 4500 to 4800 psi were obtained when heating either by thermal radiation or by bombardment with beams oscillating at 20, 60, or 3000 cps (see Table 1). The values of the elongation to ultimate strength were approximately the same for all of the tests. Although total elongations indicate an effect, subsequent tests yielded so much scatter in these values that no significance is attached to them. It should be noted that no surface damage of the type shown in Fig. 3 occurred on any of the surfaces in the short-time tests (4 to 7 min).

In the second experiment no effect of prolonged bombardment using high-frequency sweeps was observed on the tensile strengths, as may be seen in Table 2. Specimens that were heated at 2400°C for 30 min prior to testing either by 3000-cps bombardment or by thermal radiation were identical in surface appearance and had nearly equal ultimate tensile strengths, when compared at each test temperature. However, material that had been heated at 2400°C by beams oscillating at 60 cps was visibly damaged and, as seen in Fig. 4, showed a reduction in strength as compared to normal specimens (*i.e.* those heated by thermal radiation). At room temperature the relative reduction was 62 percent, and at 1200°C it was 7 percent. There was considerable scatter in the data at 2200°C, but the average of all tests showed a relative reduction in strength of 3 percent.

The slightly higher strength of specimens B2 compared to B1 was apparently related to their greater thickness. Although heat C was somewhat stronger than heat B, the response of the two heats to the experimental conditions was similar. Even though the room-temperature strengths of the recrystallized tungsten used here were less than those usually reported, the values obtained were very consistent. The average values of elongations to ultimate tensile stress were greater at 1200°C than at 2200°C. Total elongations showed considerable scatter, however, so that no trends were evident in these data.

Thus it appears that bombardment during deformation, when flow mechanisms are active, does not influence mechanical properties. Also,

TABLE 1
Comparison of Tensile Properties of Tungsten* at 2200°C
When Heated by Thermal Radiation and Electron Bombardment

Means of Heating	Ultimate Tensile Strength† (psi)	Elong. to UTS (%)	Total Elong. (%)
Thermal Radiation	4800	13	22
Electron Beams Oscillating at 20 cps	4800	14	25
Electron Beams Oscillating at 60 cps	4700	14	37
	4500	11	35
Electron Beams Oscillating at 3000 cps	4800	11	34
	4800	13	37

*Heat A, recrystallized at 2500°C for 30 min by thermal radiation heating.
†Crosshead speed: 0.05 in./min.

prolonged bombardment that does not produce surface damage prior to a test, does not appear to change the gross flow process. If unobservable surface changes were present, they did not influence mechanical properties.

Metallography

The surface and microstructures of tungsten, after heating at 2400°C either by electron bombardment at 3000 cps or by thermal radiation, were identical. In subsequent tensile tests, both groups of specimens failed in the same manner and showed similar surface and fracture features characteristic of the temperature at which the tests were conducted. Specimens heated at 2400°C by 60-cps bombardment, all of which were visibly damaged, showed basically the same characteristics of deformation and fracture at each test temperature as those heated by thermal radiation.

Because recrystallized tungsten is very brittle and notch sensitive at room temperature, and because the damage to tungsten consisted largely of grain boundary cracks about 0.005 in. deep, it was not surprising to find a large reduction in strength at room temperature. Although the cracks probably provided stress concentrations that promoted cleavage, the exact origin of the fracture could not be determined by fractographic examination.

Above the transition temperature, tungsten is ductile and the effect of the grain boundary cracks is less pronounced. At 1200°C these cracks appear to open up during extension (Fig. 5) and may contribute to a reduction of the cross-sectional area. Nevertheless, all failures occurred by grain deformation and the subsequent necking to a knife-edge fracture. The density of surface slip markings was the same on all specimens tested at 1200°C.

At 2200°C intergranular voids developed throughout the test section and failure occurred intergranularly, even though a relatively high strain rate was used (Fig. 6). The opening of grain boundary cracks of damaged surfaces was evident at this temperature also. Since intergranular cracks appear at the surface as well as the interior, the contribution to reduced strength of a few additional damage cracks might be expected to be only small, as was found. The density of surface slip markings developed in all tests at 2200°C was the same, although less than that at 1200°C.

In tests at 2200°C, during which either thermal radiation or bombardment heating was employed, intergranular voids were formed and failures occurred intergranularly, as shown by the example in Fig. 6. The density of slip markings, as well as the appearance of the surfaces, was independent of the mode of heating.

Although thermal radiation and bombardment differ in nature, they may be considered equivalent for the purpose of mechanical testing, as was assessed by the comparison of deformation and fracture characteristics as well as tensile strengths of tungsten.

TABLE 2
Effect of Pretest Electron Bombardment Heating at 2400°C on the Tensile Properties of Tungsten* at Room Temperature, 1200, and 2200°C

Test Temperature	Methods of Heating at 2400°C for 30 Min Prior to Testing											
	Thermal Radiation				Oscillating Beam at 3000 cps				Oscillating Beam at 60 cps†			
	Heat	Ultimate Tensile Strength (psi)‡	Elong. to UTS (Percent)	Total Elong. (Percent)	Heat	Ultimate Tensile Strength (psi)‡	Elong. to UTS (Percent)	Total Elong. (Percent)	Heat	Ultimate Tensile Strength (psi)‡	Elong. to UTS (Percent)	Total Elong. (Percent)
Room Temperature	B1	37,000	0	0	B1	37,900	0	0	B1	13,900	0	0
	B1	37,500	0	0	B1	35,800	0	0				
									B2	14,800	0	0
1200°C Heated by Thermal Radiation	B1	19,900	22	28	B1	19,400	21	30	B1	18,100	27	35
					B1	19,400	17	22				
					B2	20,700	24	30	B2	19,300	24	29
2200°C Heated by Thermal Radiation	B1	5,000	11	29	B1	5,000	17	32	B1	4,300	20	38
					B2	4,800	18	44	B2	4,800	16	22
					C	5,500	12	30	C	5,700	12	30
					C	5,800	13	30	C	5,500	12	29
									C	5,200	14	32

*Recrystallized at 2500°C for 30 min by thermal radiation heating.
†Specimens heated by 60-cps oscillating beams were visibly damaged (see Fig. 3).
‡Crosshead speed: 0.05 in./min.

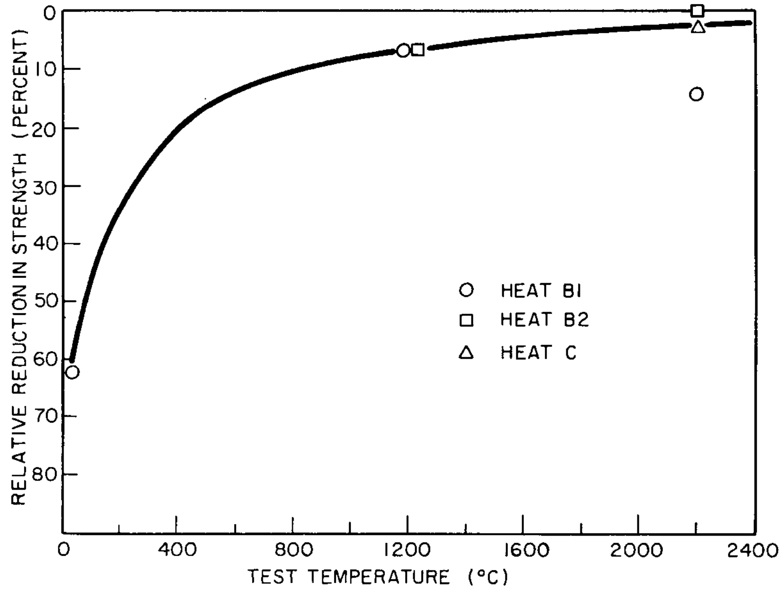

Fig. 4 — Relative reduction in strength of damaged tungsten specimens as a function of test temperature. The relative reduction (in percent) is given by

$$\left(\frac{\text{normal strength} - \text{damaged strength}}{\text{normal strength}}\right) \times 100.$$

The strength values used were the averages for each of the heats.

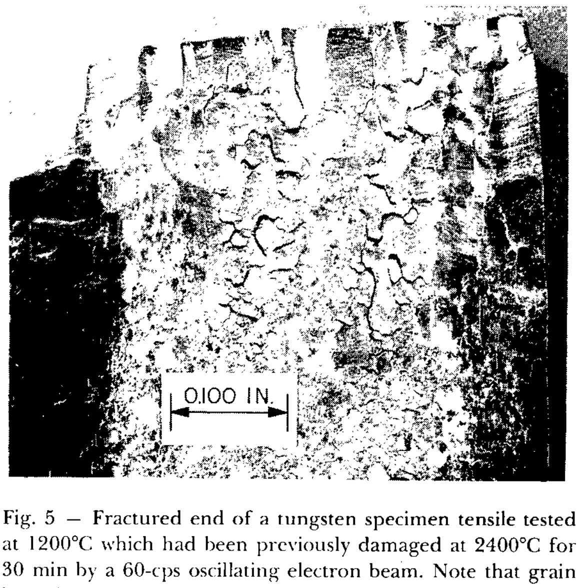

Fig. 5 — Fractured end of a tungsten specimen tensile tested at 1200°C which had been previously damaged at 2400°C for 30 min by a 60-cps oscillating electron beam. Note that grain boundary cracks opened during deformation. (Original magnification 8X.)

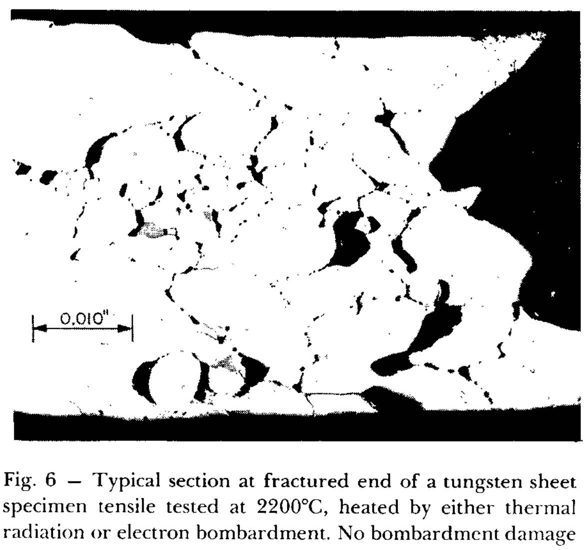

Fig. 6 — Typical section at fractured end of a tungsten sheet specimen tensile tested at 2200°C, heated by either thermal radiation or electron bombardment. No bombardment damage took place on the surface during the test at 2200°C. (Original magnification 100X.)

SUMMARY AND CONCLUSIONS

The suitability of electron bombardment was examined as a means of heating for the evaluation of mechanical properties of refractory metals at very high temperatures. An electron beam furnace attached to an Instron tester permitted tensile tests up to 2760°C. Temperature measurement and control were accomplished using optical and two-color pyrometry. An extensometer was adapted to the furnace to measure strain, and it employed a linear differential transformer enclosed in a water-cooled jacket.

The influences of bombardment, including surface damage and more subtle effects, on mechanical properties were investigated by comparing ultimate tensile strengths of tungsten heated by thermal radiation and by electron bombardment.

The significant findings are as follows:

1. Electron bombardment heating and thermal radiation heating during tensile tests at 2200°C gave the same ultimate strengths. The surface appearances of the failed specimens were the same.

2. Heating for a prolonged period, prior to testing, either by thermal radiation or by bombardment that did not produce any visible surface changes gave the same ultimate tensile strengths when compared at room and high temperatures.

3. Only that material which was visibly damaged by low-frequency oscillating beams showed a reduction in strength, which was greatest at room temperature and became less at higher temperatures. At 2200°C the apparent strength reduction, if not attributable to scatter in the data, was very small.

These findings suggest that, when applied to mechanical property tests, electron bombardment heating that does not produce visible surface damage may be considered equivalent to thermal radiation heating.

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13. ABSTRACT

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