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EFFECT OF DUCTILE CLADDING ON THE BEND TRANSITION TEMPERATURE OF WROUGHT TUNGSTEN*

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SUMMARY

A ductile cladding was applied to tungsten in order to determine if such a ductile surface layer would lower the ductile-brittle transition temperature of tungsten. Copper was selected for the cladding and was applied by hot roll bonding at 1040° C. The bend transition temperatures were determined for 0.020-inch- (0.051-cm) thick tungsten sheet clad with 0.00025- to 0.020-inch- (0.0006- to 0.051-cm) thick copper.

A decrease in the ductile-brittle bend transition temperature was observed for the clad tungsten in both the longitudinal and transverse directions. Intermediate cladding thicknesses (0.001 to 0.005 in. (0.0025 to 0.013 cm)) yielded the largest decreases. The reduction in transition temperature is thought to be caused primarily by compressive stresses generated in the tungsten during cooling from the roll-bonding temperature. These stresses are the result of the differential thermal contraction of the tungsten and the copper. The cladding also appeared to have slightly improved the ductility of the tungsten, particularly in the transverse direction, by minimizing the effect of surface imperfections.

INTRODUCTION

The current need for metals that can withstand high temperatures has increased the interest in refractory metals. Tungsten is of particular interest because it has the highest melting point (~3410° C) of any metal. Unfortunately, commercial tungsten has a ductile-brittle transition temperature which can be as much as several hundred degrees above room temperature (ref. 1).

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*Part of the information presented herein was submitted as a thesis in partial fulfillment of the requirements for a Master of Science degree at the Case Institute of Technology, Cleveland, Ohio, June 1966. Prof. John F. Wallace was the thesis advisor for this work.

The transition temperature of tungsten can be reduced somewhat by additional purification. The transition temperature also can be influenced by the same variables that affect the transition temperature of ferritic steels (ref. 2). These variables include both internal structural variables (such as grain size and preferred orientation) and external mechanical variables (such as the presence and size of surface defects and other stress concentrators and the type of surface finish).

The effect of surface finish on the transition temperature of tungsten has been studied in detail (refs. 3 to 6), and the studies indicate that a finer surface finish results in a lower transition temperature. The decrease is attributed primarily to the removal of minute surface imperfections rather than to the removal of a contaminated layer from the surface.

It has been found that a decarburized surface on steel can improve notch toughness by lowering the hardness at the surface, thus allowing plastic bending at the notch (ref. 7). This effect suggests that the application of a ductile surface cladding to tungsten might minimize the effect of minute surface imperfections (i.e., produce surface healing) and thus lower the ductile-brittle transition temperature.

Another surface effect that has been observed in steel, as well as in many other metals, is that residual compressive stresses at the surface improve the fatigue resistance of the material. These residual compressive stresses reduce the effective tensile stresses produced at the surfaces during the fatigue test and thus minimize the formation of surface cracks. If compressive stresses could be generated in tungsten, the effect of surface imperfections on transition temperature might be minimized. One reported attempt to reduce the transition temperature of tungsten by shot peening was unsuccessful (ref. 5). Possibly, however, compressive stresses could be obtained in tungsten by cladding the surface of the tungsten with a metal having a different thermal expansion coefficient, providing the proper cladding technique is used.

The study reported herein was conducted to determine if either of the two mechanisms proposed above (i.e., compressive stresses or surface healing) could appreciably lower the bend transition temperature of tungsten. This work consisted of cladding tungsten with copper and measuring the bend transition temperature of the clad samples. An effort was made to separate the effects of surface healing from those of residual compressive stresses.

EXPERIMENTAL PROCEDURE

Selection of Cladding Material and Cladding Technique

To study the effect of a ductile cladding on tungsten, a cladding metal that was mutually insoluble with tungsten was desirable in order to avoid masking the effect of the cladding by possible alloying influences. This requirement limited the choice of cladding, since only a few metals (such as copper, gold, silver, and zinc) are mutually insoluble in tungsten (refs. 8 and 9). Copper was selected because it is readily available, inexpensive, and ductile at room temperature, and has a much greater (about four times) thermal expansion coefficient than tungsten.

Although copper and tungsten are reported to be mutually insoluble, molten copper is known to wet tungsten. Thus, an adherent copper cladding on tungsten appeared to be feasible. However, cladding the samples with molten copper was not attempted because the thickness and uniformity of the cladding obtained with this technique might present control problems. Instead, various other cladding methods were investigated. Preliminary attempts to electroplate copper on tungsten resulted in a nonadherent plate that could be easily peeled from the tungsten substrate. Thus, work was discontinued on this cladding method. A high-temperature roll-bonding process was investigated and proved to be capable of providing an adherent copper cladding of uniform thickness. Based on these initial results, the roll-bonding process was selected as the cladding method to be used in this study.

Materials

Commercial, sintered and wrought tungsten sheet with a purity of 99.9 percent or higher was used in the study. The major portion of the investigation was conducted on tungsten sheet with an initial thickness of 0.030 inch (0.076 cm). All specimens for these tests were cut from one sheet of tungsten to provide uniform purity and processing history throughout the investigation.

Commercial, oxygen-free copper sheet, with a purity of 99.95 percent or better, was used for the cladding. The copper sheet was originally 0.032 inch (0.081 cm) thick and was cold-rolled to the various thicknesses required.

Rolling Equipment and Procedure

The specimens used in the roll bonding of copper to tungsten consisted of 1.0 by 3.0 inch (2.5 by 7.6 cm) tungsten coupons sandwiched between sheets of copper, with the 3.0-inch (7.6-cm) direction corresponding to the original rolling direction of the tungsten sheet. Prior to assembly, both metals were sanded with 180-grit paper to remove surface oxides, washed with water, and rinsed in acetone. Copper sheet then was formed around the tungsten cores, as shown in figure 1.

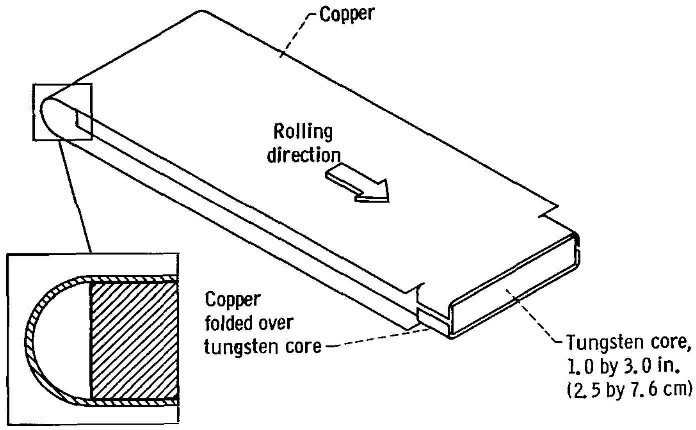


Figure 1. - Schematic drawing of tungsten-copper assembly prior to rolling.

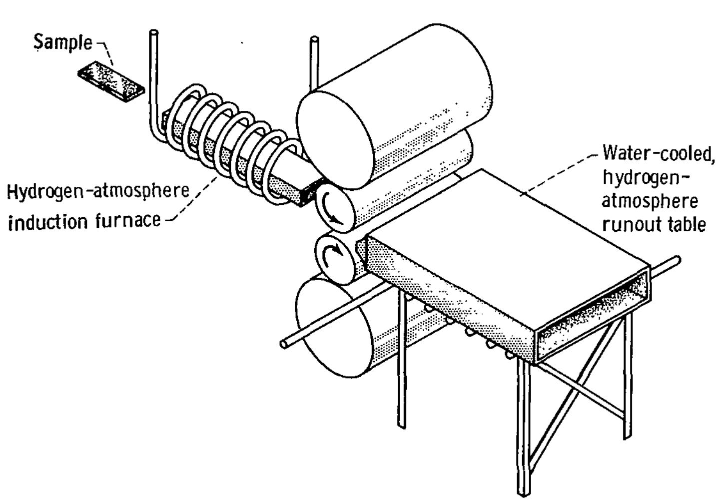


Figure 2. - Schematic drawing of rolling equipment.

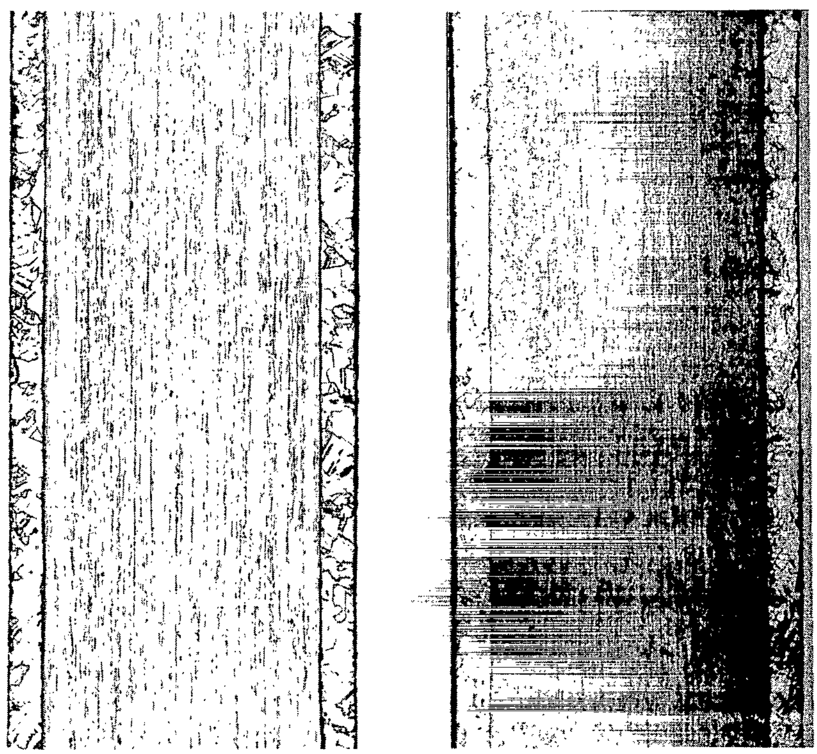
The tungsten-copper assembly was heated to the desired rolling temperature in an inductively heated, hydrogen-atmosphere furnace, which was mounted directly in front of a four-high rolling mill with 8-inch- (20-cm) wide rolls. After a 2-minute soak at temperature, the assembly was pushed from the furnace directly into the rolls, with an estimated transfer time of less than 1/4 second. A roll speed of 100 feet (30 m) per minute was used throughout the investigation. After rolling, the samples dropped onto a hydrogen-atmosphere, water-cooled runout table and were cooled to room temperature in less than 10 seconds. A schematic drawing of the furnace, the rolling mill, and the runout table is shown in figure 2.

Various rolling temperatures from 720° to 1040° C were investigated in order to determine the optimum temperature for roll bonding copper to tungsten. The results indicated that the highest rolling temperature investigated (1040° C) yielded the best bonding; therefore, this rolling temperature was used throughout the remainder of the investigation. Bonding at temperatures higher than 1040° C was not attempted because of possible melting of the copper (melting point, 1083° C).

Rolling Schedule

The rolling schedule that was utilized for most copper claddings, up to 0.005 inch (0.013 cm) in thickness, consisted of a 5 percent reduction in total thickness on the initial pass, followed by 10 percent reductions on all subsequent passes until a total reduction of about 30 percent had been attained on the tungsten. The copper, being softer, was reduced about 50 percent in thickness because it tended to extrude off the substrate during rolling. Various starting thicknesses of copper were used so that the desired cladding thickness was obtained without exceeding a 30-percent reduction of the tungsten.

Typical longitudinal and transverse microstructures of a sample with a cladding applied by this process are shown in figure 3. The tungsten core had a heavily cold-worked



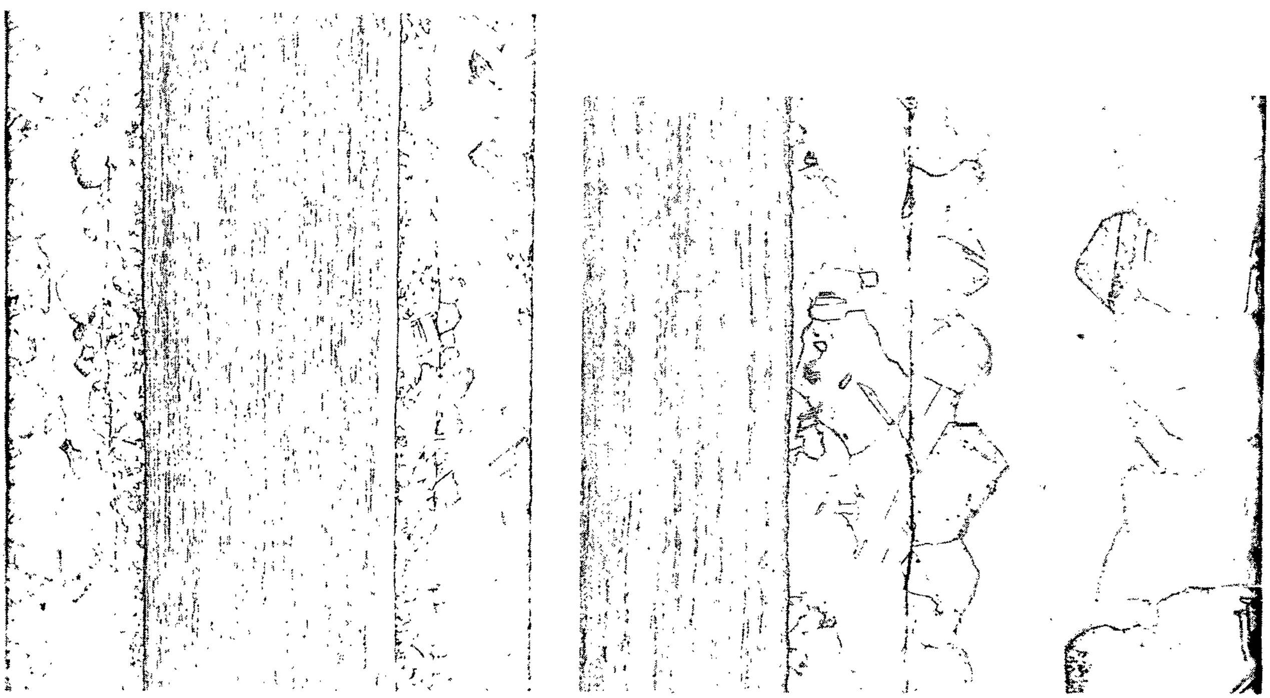
(a) Longitudinal. (b) Transverse. C-66-1775

Figure 3. - Typical microstructures of roll-clad, 0.020-inch-(0.051-cm) thick tungsten samples with 0.0025-inch-(0.006 cm) thick copper cladding applied by one-layer process. Etchant, ammonium hydroxide and hydrogen peroxide ($NH_4OH+H_2O_2$). X75.

structure, whereas very little working is evident in the copper cladding. No diffusion or other reaction was observed at the copper-tungsten interface.

Room-temperature peel tests performed on samples clad by the rolling schedule described previously gave qualitative evidence of the good bond at the copper-tungsten interface. These tests resulted in delamination of the tungsten substrate rather than in failure of the interface bond.

Adequate bonding could not be obtained, however, for claddings thicker than 0.005 inch (0.013 cm). The thicker claddings presumably reduced the rolling stresses at the copper-tungsten interface below that necessary for bonding. Therefore, various modifications of the original rolling schedule were investigated in an effort to improve the bonding of the thicker claddings. In the method that yielded the best results of those investigated, the copper cladding was applied in two separate layers. A thin, initial layer of copper was applied to the tungsten, and the samples were rolled, using the rolling schedule described previously, until the tungsten substrate was within 0.001 inch (0.003 cm) of the final thickness. This initial layer of cladding was 0.0025 inch (0.006 cm) thick after rolling. Then, to obtain the cladding thickness desired, an additional layer of copper was roll bonded to the thinly clad specimens using only one roll pass of about a 5-percent reduction in thickness. The additional layer of cladding bonded



(a) Magnification, X75. (b) Magnification, X250. C-66-1779

Figure 4. - Microstructures of roll-clad, 0.020-inch-(0.051-cm) thick tungsten sample with 0.010-inch-(0.025-cm) thick copper cladding applied by two-layer process. Longitudinal sections. Etchant, ammonium hydroxide and hydrogen peroxide ($NH_4OH+H_2O_2$).

readily to the initial copper cladding. Only one roll pass was used because reheating the thickly clad samples to the rolling temperature resulted in failure of the initial copper-tungsten bond. Presumably, this failure is caused by stresses generated at the interface by the differential thermal expansion of the cladding and the substrate.

Because of the rolling schedule used, the samples clad by the two-layer process were at an elevated temperature for only a short time (< 5 sec) after the copper-copper bond was achieved. Thus, little diffusion could take place across the copper-copper interface, and, as a result, the interface was marked by a line of discontinuous grain growth and porosity, as shown in figure 4. We believe that the bonding across the interface, however, was relatively good, as evidenced by the fact that no copper-copper bond failures were detected throughout the entire investigation.

Specimen Types

The thickness of the tungsten substrate after rolling for all the bend-test specimens was 0.020 inch (0.051 cm), and the cladding thickness varied from 0.00025 to 0.020 inch (0.0006 to 0.051 cm) per side. In all cases, the cladding thickness was within ±0.0005 inch (0.0013 cm) of the desired thickness. Samples with cladding thicknesses of 0.0025 inch (0.006 cm) or less were fabricated by using a single-layer process, and samples with cladding thicknesses greater than 0.0025 inch (0.006 cm) were generally fabricated by the two-layer process. Samples with 0.005-inch- (0.013-cm) thick cladding, however, were fabricated by both techniques in order to determine the influence of the different cladding procedures on the transition temperature. After rolling, all the samples were relatively flat, and did not require straightening.

Unclad tungsten samples were employed as control specimens to determine the effectiveness of the copper cladding. These unclad tungsten coupons were rolled using a reduction schedule similar to that used for the single-layer copper-clad samples. The only difference in the procedure was that the unclad samples were not sanded prior to rolling. This difference was presumed to have little effect on the transition temperature of the as-rolled material.

In addition to the previously described samples, a small number of other samples, both clad and unclad, were produced to help explain certain of the test results. These samples are described in the RESULTS AND DISCUSSION section.

Bend Tests

The bend transition temperatures of the unclad and clad tungsten sheet samples were determined in both the longitudinal and transverse directions using specimens 0.5 inch wide by 1.0 inch long (1.3 by 2.5 cm). The 1.0-inch (2.5-cm) dimension of the bend-test specimens was parallel to the rolling direction for the longitudinal tests and was perpendicular to the rolling direction for the transverse tests. Prior to testing, the edges of the specimens were sanded with 280-grit paper to minimize any edge defects. The specimens were tested by three-point loading in a tensile machine at a crosshead speed of 2 inches (5 cm) per minute. The bend test was terminated automatically when a bend angle of 105° was achieved, and the transition temperature was arbitrarily defined as the lowest temperature at which the samples could be bent at least 90° without cracking. Failure of the samples was detected audibly. The estimated accuracy of the transition temperatures determined in this study was $\pm 2^{\circ}$ C.

All tests above room temperature were performed in air in a resistance-heated furnace. For tests below room temperature, the bend-test assembly was immersed in an acetone - dry ice bath. Temperatures were monitored with a Chromel-Alumel thermocouple mounted on the plunger. A schematic drawing of the bend-test assembly is shown in figure 5.

The copper cladding on the samples was expected to behave in a ductile manner, and any failures were expected to be initiated in the tungsten. With this reasoning in mind, most of the bend tests were conducted with the centerline bend radius held constant so that the tungsten in all the samples would be subjected to similar amounts of strain regardless of the thickness of the cladding. A centerline bend radius of 0. 120 inch (0. 305 cm) was utilized. To maintain this centerline radius, the plunger bend radius was varied to compensate for differences in cladding thickness. A few tests also were conducted in which the bend-radius to overall-thickness ratio was held constant at 4. 5.

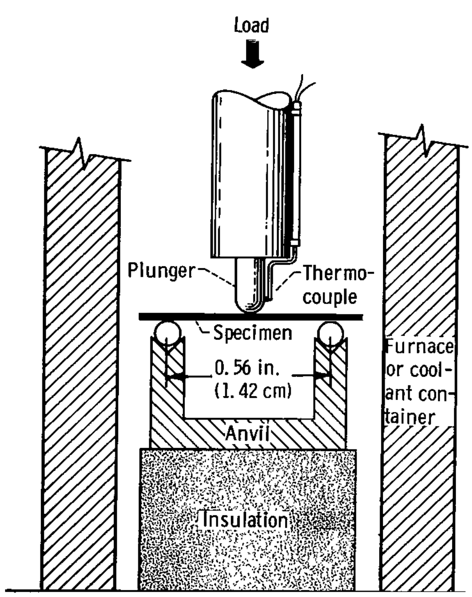


Figure 5. - Schematic drawing of bend-test apparatus.

RESULTS AND DISCUSSION

Bend Tests

Effects of cladding thickness. - The effects of cladding-thickness variations on the bend angle of roll-bonded, copper-clad, 0.020-inch- (0.051-cm) thick tungsten samples as a function of temperature are shown in figure 6 for samples with cladding thicknesses up to 0.020 inch (0.051 cm). In general, the cladding reduced the transition temperature of the tungsten in both the longitudinal and transverse directions. For the same cladding thickness, the cladding applied in one layer appeared to be somewhat more effective in reducing the transition temperature than the cladding applied in two layers, as indicated in figure 6(a), in the two curves for 0.005-inch (0.013-cm) cladding. Since these two samples were similar with respect to surface condition and cladding thickness, the difference in transition temperature must be the result of the cladding process, as is discussed later in this section.

Plotting the transition temperature of the clad samples as a function of cladding

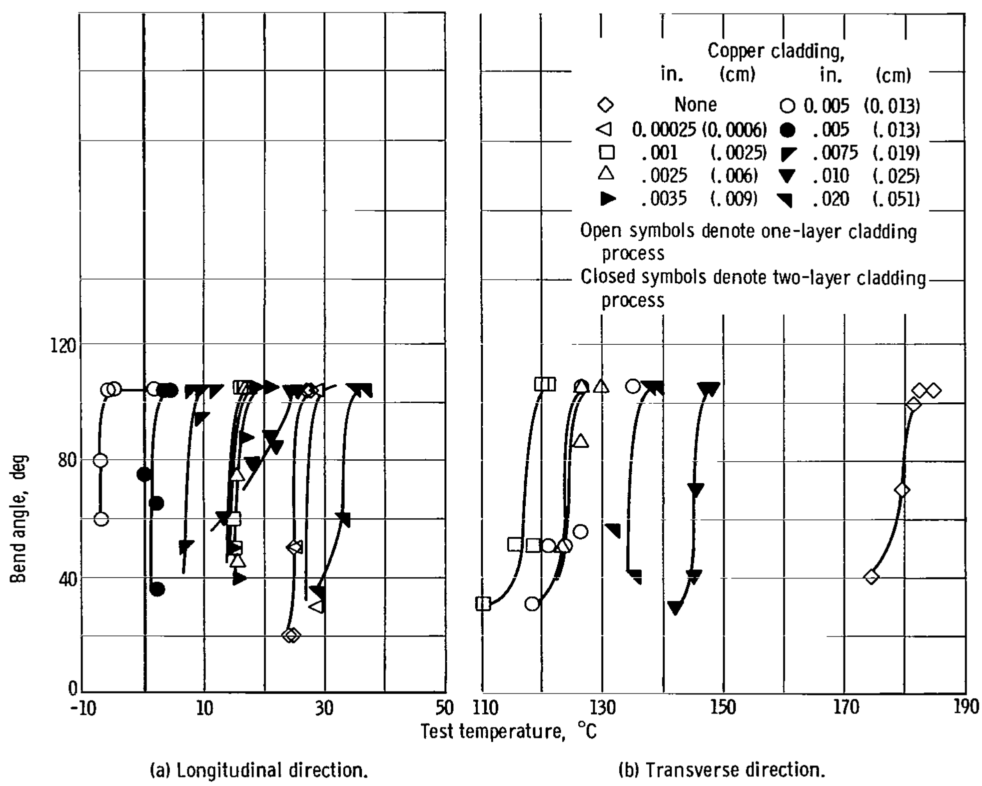
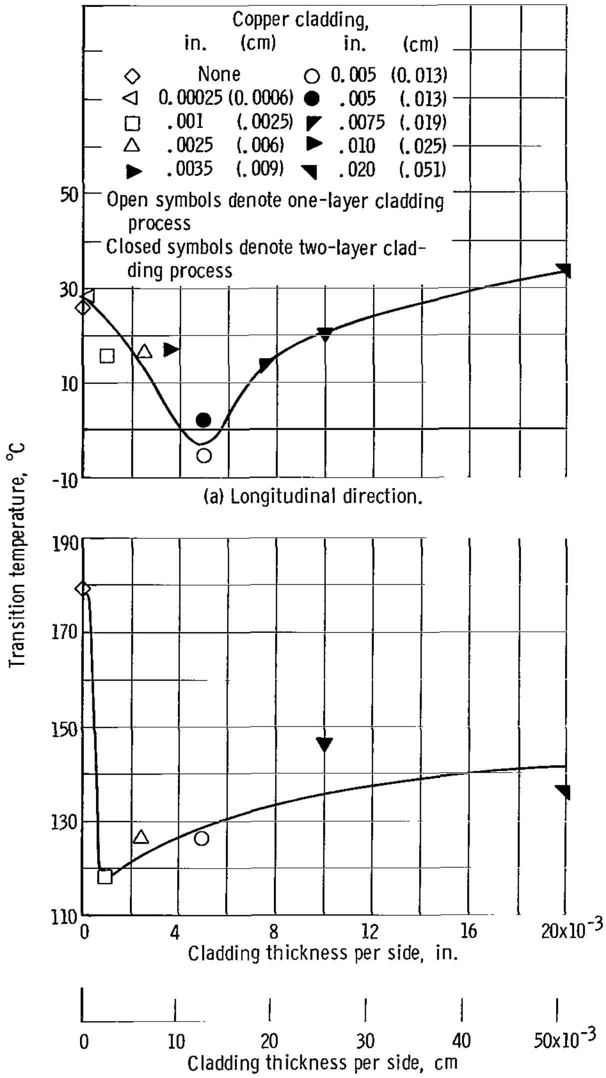


Figure 6. - Effect of test temperature on bend angle of roll-clad 0.020-inch- (0.051-cm) thick tungsten with copper-cladding thicknesses of 0.00025 to 0.020 inch (0.0006 to 0.051 cm) per side. Centerline bend radius for all tests, 0.120 inch (0.305 cm).



(a) Longitudinal direction.

(b) Transverse direction.

Figure 7. - Effect of copper-cladding thickness on transition temperature of roll-clad, 0.020-inch- (0.051-cm) thick tungsten. Centerline bend radius for all tests, 0.120 inch (0.305 cm).

thickness resulted in the curves shown in figure 7. A minimum transition temperature can be observed for both specimen orientations, occurring at a cladding thickness of about 0.005 inch (0.013 cm) for the longitudinal direction (fig. 7(a)) and 0.001 inch (0.0025 cm) for the transverse direction (fig. 7(b)).

At least two opposing factors must be influencing the transition temperature of the samples for each curve to go through a minimum. The decrease in transition temperature with thin cladding thicknesses is thought to be the result of residual compressive stresses generated in the tungsten and/or the healing of surface imperfections. The increase in transition temperature with increasing cladding thickness, however, is not fully understood, but it may be caused by factors to be discussed later in this section.

The residual compressive stresses are generated in the tungsten substrates of the copper-clad samples as a result of the large difference in the thermal expansions of copper and tungsten. If these metals are bonded together at high temperature and then cooled, the copper tries to contract much more than does the tungsten. Thus, residual stresses are generated in both substrate and cladding (compressive stresses in the tungsten and tensile stresses in the copper). Because of the residual compressive stresses, the surface of the tungsten substrate of the clad samples should be subjected to lower tensile stresses than the unclad samples during bend testing. As a result, there should be less tendency for crack formation and propagation in the clad samples, and thus the transition temperature should be lower. Since the residual stress in the tungsten should be a function of the cladding thickness, the transition temperature should decrease with increasing cladding thickness, as in the initial portion of the curve shown in figure 7(a).

Differences in residual stresses probably caused the difference in the transition temperature of the two samples that had the same cladding thickness (0.005 in. (0.013 cm)) but were clad by either the one- or two-layer process (fig. 6(a)). In the two-layer process, some cooling of the second layer of cladding occurs prior to bonding because of radiant heat loss and contact with the rolls. The cooling results in some contraction of the second layer of cladding before bonding, and thus less residual stress is developed than with the single-layer process. Cooling of the cladding prior to bonding also occurs in the single-layer cladding process. After the initial bonding pass, however, the single-layer-clad samples are reheated for additional rolling. Plastic flow of the copper occurs at the rolling temperature and permits the samples to return to an essentially stress-free condition at temperature. Then, with bonding already achieved, rapid cooling of the clad sample results in greater residual stresses.

Filling or healing of surface imperfections in the tungsten with copper also might lower the transition temperature by minimizing stress concentrations due to the imperfections. In this case, the transition temperature should decrease markedly with the initial application of cladding and then remain relatively unaffected by additional cladding. The initial part of the curve in figure 7(b) suggests this type of behavior. Additional evidence of residual compressive stresses and surface effects is given in the section Analysis of Cladding Effects, along with attempts to separate the relative effectiveness of these factors.

One possible explanation for the unexpected increase in transition temperature with greater cladding thicknesses is that the neutral axis does not remain at the original mid-thickness of the sample during plastic bending, as it does for elastic bending. Instead, the neutral axis shifts closer to the concave side of the bend. This shift is more pronounced on the more thickly clad samples, and thus the outer fibers of the tungsten are subjected to increasing tensile stresses as the cladding thickness is increased. As a result, there is an apparent increase in transition temperature.

Effect of bend-radius to overall-thickness ratio. - In the preceding tests the centerline bend radius of the tungsten substrate was held constant, but the actual bend-radius to overall-thickness ratio decreased with increasing cladding thickness. This ratio decreased from 5.5 for the unclad 0.020-inch- (0.051-cm) thick tungsten to 1.5 for samples having a 0.020-inch- (0.051-cm) thick copper cladding. According to established metal-forming data on bending (ref. 10, pp. 557-562), a decrease in this ratio can cause a decrease in the bend angle obtainable for any given material.

To help resolve the effect of bend radius on transition temperature, additional tests (in the longitudinal direction only) were conducted in which the bend-radius to overall-specimen-thickness ratio was held constant at 4.5. The results of these tests are shown in figure 8. In this case, the transition temperature does not show a minimum when plotted against the cladding thickness. The transition temperature, instead of decreasing continuously with increasing cladding thickness as might be expected, appears to approach some limiting value. The reason for this trend is not clear. One possible explanation is that the cooling rates of the thickly clad samples were not fast enough to prevent some annealing of the copper claddings after rolling. Thus, the expected increase in residual stress resulting from the thicker claddings was offset by a reduction in residual stress caused by annealing. As a result, the transition temperature approaches a limiting value.

Both types of bend tests described previously (i.e., either constant-centerline-radius

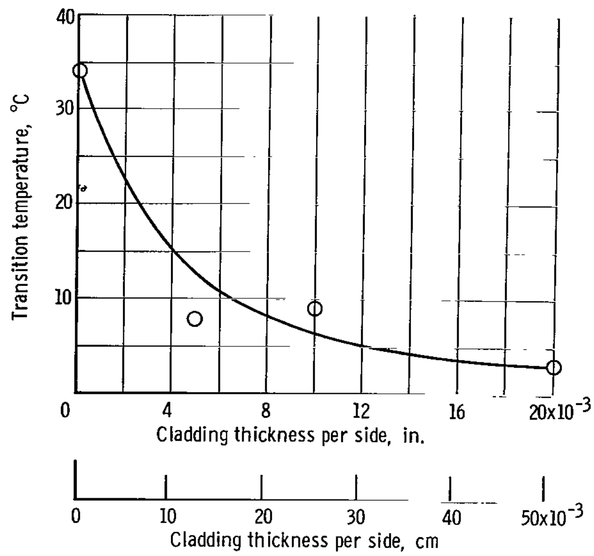


Figure 8. - Effect of copper-cladding thickness on transition temperature of roll-clad, 0.020-inch- (0.051-cm) thick tungsten, tested in longitudinal direction at constant bend-radius to overall-thickness ratio of 4.5. All samples clad by two-layer process.

or constant-bend-radius ratio) indicate that the copper cladding could reduce the transition temperature of tungsten. Because of test deficiencies, however, the actual behavior of the clad samples could not be determined. In the constant-centerline-radius tests, the shift in the neutral axis during bending subjected the tungsten to additional strain as the cladding thickness increased. For the constant-bend-radius-ratio tests, the centerline bend radius increased with increasing cladding thickness; therefore, the strain experienced by the outer fibers of the tungsten during bending decreased with increasing cladding thickness. To determine the actual bend-transition-temperature behavior of the clad samples, bend tests should be conducted so that the actual strain encountered by the tungsten fibers during bending would be identical for all samples. The development of such a test, however, was beyond the scope of this study.

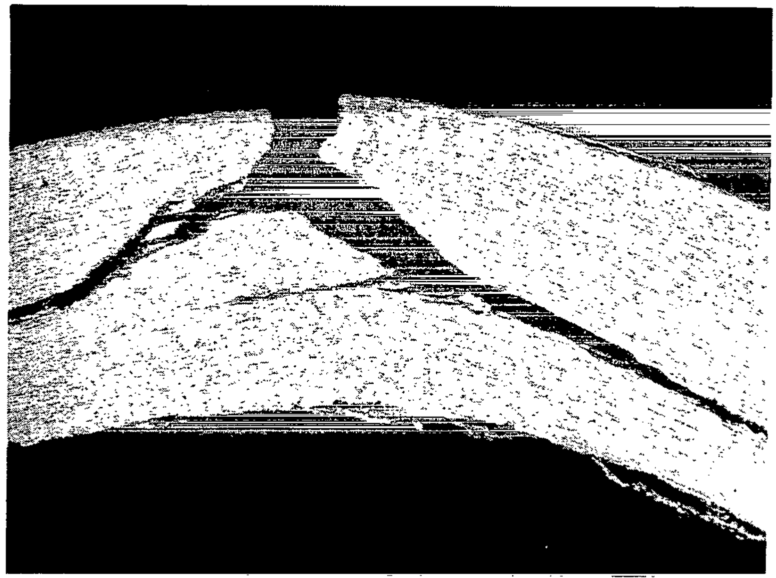
Metallographic studies. - Metallographic examination of selected fractures in unclad and clad bend specimens indicated that the cladding had no apparent effect on the actual mechanism of failure. Typical fractures in unclad and clad samples are shown in figure 9. In both cases, the fracture is a combination of cleavage and intergranular cracking. The microstructure of the clad sample (fig. 9(b)) indicates that the fracture initiated in the tungsten, after which, the copper necked. Examination of the successfully bent samples, even those tested at low temperatures, showed no evidence of cracking or delamination of the tungsten.

Analysis of Cladding Effects

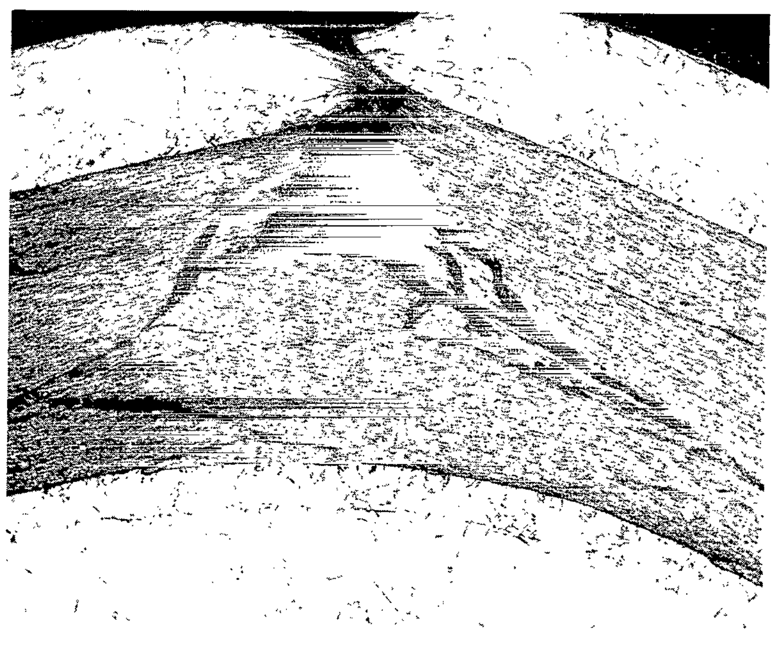
Residual stresses. - If the residual stresses in the clad samples could be reduced by annealing, the copper cladding would be expected to exert a smaller influence on transition temperature. Accordingly, both clad and unclad samples were annealed in hydrogen at 980° C for 2 hours and furnace cooled to room temperature at a rate of 40° C per hour. (The slow cooling rate was used to minimize the formation of residual stresses during cooling.) The tungsten thickness for all the samples was 0.020 inch (0.051 cm). The cladding thicknesses selected for each test orientation were 0.005 inch (0.013 cm) for the longitudinal direction and 0.0025 inch (0.006 cm) for the transverse direction. The samples with the 0.005-inch- (0.013-cm) thick cladding were clad by the two-layer process.

Examination of the clad samples after annealing showed no evidence of bond failure. The copper-copper interface of the sample clad by the two-layer process was completely eliminated by the anneal (fig. 10). Even after annealing, no copper-tungsten interface reaction can be detected.

The bend transition temperatures of the samples after annealing are listed in table I. Also included are the results obtained on the as-rolled material. Annealing at 980° C

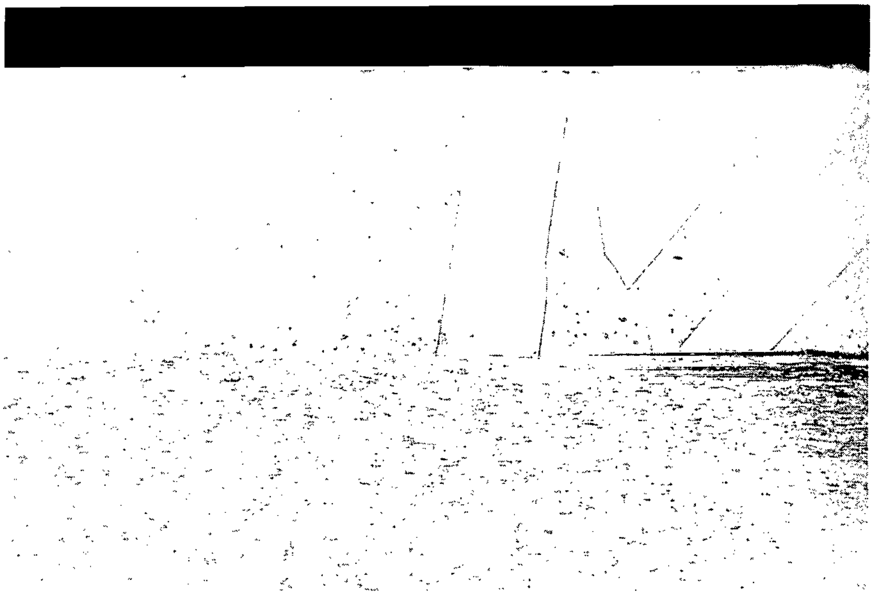


(a) Unclad.



(b) Cladding, 0.010 inch (0.025 cm) thick per side. C-66-1780

Figure 9. - Comparison of fractures of clad and unclad 0.020-inch-(0.051-cm) thick tungsten near bend transition temperature. Tested in transverse direction. Etchant, ammonium hydroxide and hydrogen peroxide ($NH_4OH+H_2O_2$). X75.



C-66-1777

Figure 10. - Transverse cross section of copper tungsten sample clad by two-layer process. Sample annealed at 980° C for 2 hours. Etchant, ammonium hydroxide and hydrogen peroxide ($NH_4OH+H_2O_2$). X250.

TABLE I. - BEND TRANSITION TEMPERATURES OF UNCLAD AND COPPER-CLAD TUNGSTEN IN THE AS-ROLLED OR ANNEALED CONDITIONS

[Tungsten thickness, 0.020 in. (0.051 cm); centerline bend radius for all samples, 0.120 in. (0.305 cm).]

Cladding thickness per side		Condition	Longitudinal test direction	Transverse test direction
in.	cm		Transition temperature, °C	
None	None	As-rolled	26	179
None	None	[a]Annealed	69	145
0.0025	0.006	As-rolled	--	126
.0025	.006	Annealed	--	136
.005	.013	As-rolled	2	---
.005	.013	Annealed	68	---

[a]Samples annealed in hydrogen at 980° C for 2 hr.

increased the transition temperature of the unclad tungsten from 26° to 69° C in the longitudinal direction and lowered it from 179° to 145° C in the transverse direction. Since these samples were used only as control specimens in determining the relative effectiveness of the annealed copper claddings, no attempt was made to determine the cause of the changes observed in the bend transition temperatures of the unclad, annealed samples. Possibly, however, these changes may be explained on the basis of stress relieving.

For the clad specimens, annealing reduced the effectiveness of the copper cladding. In the longitudinal test direction, the 0.005-inch (0.013-cm) cladding reduced the transition temperature of the as-rolled sample by about 24° C. In the annealed condition, the cladding had little effect, with both the clad and unclad specimens having about the same transition temperature. Apparently in this test direction, the reduction in the transition temperature of the as-rolled composites is caused almost entirely by residual stresses, which can be relieved by annealing.

A 0.0025-inch- (0.006-cm) thick cladding reduced the transition temperature of the as-rolled sample by 53° C in the transverse direction. In this test direction, however, the beneficial effect of the cladding apparently was not completely eliminated by annealing. The clad sample after annealing had a transition temperature about 10° C lower than the unclad annealed sample. Since the annealing treatment should have removed essentially all residual stresses, the observed decrease in transition temperature occurred presumably because the cladding reduced the effect of surface imperfections. These results indicate that the tungsten specimens were more sensitive to surface imperfections in the transverse direction or that the copper cladding was more effective in healing surface imperfections in the transverse direction.

Surface effects. - It was necessary to determine what effect the surface imperfections had on the transition temperature of unclad tungsten to determine if the copper cladding could have any surface-healing effects on the tungsten. Electropolishing has been shown to lower the transition temperature of tungsten by the removal of surface imperfections (refs. 3 to 5). Accordingly, unclad tungsten samples (0.030 in. (0.076 cm) thick) were electropolished with a sodium hydroxide solution to a thickness of 0.020 inch (0.051 cm). Unfortunately, the removal of surface imperfections is accompanied by a change in sample thickness. Additional samples were made to determine what effect a decrease in sample thickness alone would have on transition temperature. These specimens were prepared by surface grinding the 0.030-inch (0.076-cm) tungsten sheet to a thickness of 0.020 inch (0.051 cm) and then sanding with 280-grit paper. The bend specimens were positioned during sanding so that any scratches left by sanding would be parallel to the specimen length, to minimize the effects of sanding on the test results.

The bend transition temperatures of the electropolished or ground samples are listed in table II, along with the results obtained on the as-received 0.030-inch-

TABLE II. - BEND TRANSITION TEMPERATURES OF TUNGSTEN SHEET PREPARED BY VARIOUS TECHNIQUES

[Centerline bend radius for all samples, 0.120 in. (0.305 cm).]

Material and preparation	Longitudinal test direction	Transverse test direction
	Transition temperature, °C	
As-received, 0.030 in. (0.076 cm) thick	103	186
Electropolished from 0.030 in. (0.076 cm) to 0.020 in. (0.051 cm) thick	22	103
Ground from 0.030 in. (0.076 cm) to 0.020 in. (0.051 cm) thick	43	178

(0.076-cm) thick tungsten. A change in thickness alone (the ground samples) reduced the transition temperature by about 60° C in the longitudinal direction and about 8° C in the transverse direction. A similar reduction in thickness by electropolishing reduced the transition temperature an additional 21° C in the longitudinal bend direction and 75° C in the transverse bend direction. These results indicate that the tungsten used in this study was more sensitive to surface conditions in the transverse direction. Thus, any surface-healing effects caused by the cladding should be more evident in the transverse bend specimens, as was noted previously for the annealed, clad samples.

Auxiliary residual stress studies. - An additional study of the effect of annealing was conducted on two sets of 0.005-inch- (0.013-cm) thick tungsten samples clad with 0.0025-inch- (0.006-cm) thick copper on each side. These samples were 0.5 inch (1.3 cm) wide and 3.0 inches (7.6 cm) long and were produced by essentially the same roll-bonding technique that was used for the thinly clad, bend-test specimens. The 3.0-inch (7.6-cm) direction corresponded to the rolling direction of the samples. The cladding was dissolved from one side of each specimen with a nitric acid solution (the other side was protected with tape). Deflection of the specimens due to an unbalanced stress condition was measured. One set of specimens was examined after annealing under the conditions previously described. The other set of specimens was examined in the as-rolled condition.

The results of these tests confirmed the presence of residual stresses in the as-rolled samples. These samples bent toward the clad side with the average deflection being about 0.13 inch (0.33 cm) for the 3.0-inch- (7.6-cm) long specimen. No deflection was observed in the annealed specimens.

The approximate residual stress at the copper-tungsten interface of the as-rolled, copper-clad samples was calculated from the deflection data. This calculation was similar to that used in reference 10 (pp. 404 to 405) for determining the residual stress in rolled sheet, except that the equation was modified slightly to account for the difference in sample configuration. The following equation was used for the longitudinal residual stress σ_L:

$$\sigma_L = \frac{Et\delta}{(1 - \nu^2)L^2}$$

where

E Young's modulus for tungsten

L sample length

t thickness of tungsten substrate

δ deflection

ν Poisson's ratio (~0.33)

By using the deflection data from the as-rolled samples, a residual stress of about 4900 psi (33.8 MN/m^2) was obtained. The copper cladding was ignored in these calculations except as a source of residual compressive stresses at the copper-tungsten interface. Because of the assumptions made in calculating the residual stress, the value obtained must be considered as only a rough approximation.

Thermal stress calculations on the copper-clad tungsten samples indicate that the tensile stresses generated in the copper are much greater than the elastic limit of the copper. As a result, the copper cladding deforms plastically until the stress in the cladding is reduced below the elastic limit of the copper. Thus, neglecting any work hardening of the copper, the maximum stress obtainable in the cladding is approximately the elastic limit of the copper. The residual stress in the tungsten of the clad samples can be estimated by using this information and the relative areas of the tungsten and the copper. For these calculations the elastic limit of the copper was assumed to have the same value as the yield strength of copper, or 10 000 psi (68.9 MN/m^2). The cross sectional area of the tungsten in the deflection specimens described previously (after removal of the cladding from one side) was twice that of the copper cladding. Thus, a residual compressive stress of about 5000 psi (34.5 MN/m^2) should be present in the 0.005-inch- (0.013-cm) thick tungsten substrate. This value is in good agreement with the stress value obtained from the deflection measurements. From these stress results, it appears that the residual compressive stresses are small and yet have a definite effect on the bend transition temperature of tungsten.

CONCLUDING REMARKS

The reduction in bend transition temperature observed in the copper-clad tungsten samples is thought to be caused primarily by residual compressive stresses in the tungsten. The degree of residual stress in the tungsten is believed to be related to the cooling rate of the clad samples. This effect is especially true for the thickly clad samples, where the cooling rate may not be fast enough to prevent some annealing of the copper cladding after rolling. Possibly, cooling rates more rapid than those used in this experiment would allow greater residual stresses to be generated and, thus, cause reductions in transition temperatures even greater than those observed.

The ductile copper cladding had surprisingly little effect on the transition temperature of the tungsten from the standpoint of surface healing. Apparently, the low flow strength of the copper did not permit any large decrease in possible stress concentration resulting from minute surface imperfections in the tungsten. It is possible, however, that the use of a ductile cladding with a much higher flow stress than copper (such as a tungsten-rhenium alloy) could have a substantial effect on the transition temperature of tungsten.

CONCLUSIONS

The effect of a ductile cladding of copper on tungsten sheet was investigated with respect to the ductile-brittle bend transition temperature. The thickness of the tungsten core of the test samples was held constant at 0.020 inch (0.051 cm), and the cladding thickness was varied from 0.00025 to 0.020 inch (0.006 to 0.051 cm) per side. From the results presented in this study, the following conclusions were drawn:

1. Copper claddings generally reduced the bend transition temperature in both the longitudinal and transverse directions with the intermediate cladding thicknesses yielding the best results. A cladding thickness of 0.005 inch (0.013 cm) reduced the longitudinal transition temperature to about -6° C (a decrease of about 31° C compared with the unclad condition). The transverse transition temperature was reduced to about 118° C (a decrease of 61° C compared with the unclad condition) by a 0.001-inch- (0.0025-cm) thick cladding.

2. The reduction in transition temperature of the clad samples is explained primarily on the basis of the compressive stresses generated in the tungsten as a result of the differential thermal contraction of the tungsten and copper.

3. The copper cladding improved the ductility in the transverse direction to a slight extent, presumably by minimizing the effect of tungsten surface imperfections.

4. Annealing the composites, followed by slow cooling, reduced the effectiveness of the cladding in lowering the transition temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 29, 1967,
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