N73-32427

**NASA TECHNICAL NOTE**

NASA TN D-7393

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# FACTORS AFFECTING MINIATURE IZOD IMPACT STRENGTH OF TUNGSTEN-FIBER - METAL-MATRIX COMPOSITES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1973

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| 1. Report No. NASA TN D-7393 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle FACTORS AFFECTING MINIATURE IZOD IMPACT STRENGTH OF TUNGSTEN-FIBER - METAL-MATRIX COMPOSITES | | 5. Report Date October 1973 |
| | | 6. Performing Organization Code |
| 7. Author(s) Edward A. Winsa and Donald W. Petrasek | | 8. Performing Organization Report No. E-5857 |
| | | 10. Work Unit No. 501-21 |
| 9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135 | | 11. Contract or Grant No. |
| | | 13. Type of Report and Period Covered Technical Note |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546 | | 14. Sponsoring Agency Code |
| 15. Supplementary Notes | | |

16. Abstract

The miniature Izod and Charpy impact strengths of copper, copper-nickel, and nickel-base superalloy uniaxially reinforced with continuous tungsten fibers were studied. In most cases, impact strength was increased by increasing fiber or matrix toughness, decreasing fiber-matrix reaction, increasing test temperature, hot working, or heat treating. Notch sensitivity was reduced by increasing fiber content or matrix toughness. An equation relating impact strength to fiber and matrix properties and fiber content was developed. Program results imply that tungsten-alloy-fiber/superalloy matrix composites can be made with adequate impact resistance for turbine blade or vane applications.

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|---|---|---|---|
| 17. Key Words (Suggested by Author(s)) Composite; Fibers; Refractory metal; Superalloy; Foreign object damage; Izod; Charpy; Turbine blades | | 18. Distribution Statement Unclassified - unlimited | |
| 19. Security Classif. (of this report) Unclassified | 20. Security Classif. (of this page) Unclassified | 21. No. of Pages 38 | 22. Price* Domestic, $3.00 Foreign, $5.50 |

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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## SUMMARY

Miniature Izod and standard Charpy impact strength data were gathered for three continuous fiber, uniaxially reinforced composite systems; namely, tungsten (fiber)/copper (matrix), tungsten/copper-nickel, and tungsten/nickel-base superalloy. The data were then studied to ascertain how certain variables influence composite impact strength. In addition, the potential ability of tungsten-alloy/superalloy composites to meet turbine blade and vane impact strength requirements was evaluated.

The variables considered in this program had the following influence on composite impact strength. An increase in fiber or matrix toughness caused an increase in composite impact strength, while an increase in fiber-matrix reaction lowered impact strength. Increasing the fiber content either raised or lowered impact strength, but the exact effect depended on the relative toughnesses of the fibers and matrix. An empirical equation for impact strength, formally similar to the rule of mixtures equation for composite modulus, was developed. Increasing either the fiber content or matrix toughness lowered the notch sensitivity of the composite. Test temperature had a marked influence on impact strength because of a temperature sensitive ductile-brittle transition in the fibers. Hot working or heat treatment of the composite raised the impact strength of the tungsten/nickel-base superalloy composite.

The impact strength of the tungsten/nickel-base superalloy compared favorably to those of some turbine blade superalloys, and it was concluded that tungsten-alloy/superalloy composites can be made with adequate impact resistance for at least some turbine blade and vane applications. The miniature Izod impact strength of the unnotched, as-hot isostatically pressed, 60 volume percent tungsten/nickel-base superalloy ranged from 0.63 joule at 297 K to 6.8 joules at 1035 K (5.6 in.-lb at $75^{\circ}$ F to 60.3 in.-lb at $1400^{\circ}$ F); heat treatment raised it to 1.5 joules at 297 K (13 in.-lb at $75^{\circ}$ F); and hot working raised it to 3.4 joules at 297 K (30 in.-lb at $75^{\circ}$ F).

## INTRODUCTION

Materials for advanced gas turbine blades and vanes must have high stress-rupture strength, oxidation resistance, and impact damage resistance. Composite materials likely to meet the first two of these requirements have been developed at the Lewis Research Center. Petrasek and Signorelli described a tungsten - 2 thoria (fiber)/nickel-base superalloy (matrix) composite that had a 100-hour rupture strength of 338 meganewtons per square meter at 1365 K (49 000 psi at 2000° F) (ref. 1). More recently, Petrasek fabricated tungsten-hafnium-carbon/nickel-base superalloy composites whose strengths implied that 100-hour rupture strengths greater than 503 meganewtons per square meter at 1365 K (73 000 psi at 2000° F) can be achieved (unpublished data). In addition, Petrasek and Signorelli found that small thicknesses of matrix or cladding would protect tungsten fibers from oxidation in still air for 300 hours at 1365 K (2000° F). The preceding facts are encouraging. However, although tungsten/superalloy composites had good high temperature impact strength in the previous investigation, their room temperature impact strength was poor. Since this type of composite is intended for use in turbine blade and vane applications where impact damage can be a problem, it was felt that a more detailed study was needed of fiber/metal-matrix composite impact strength.

Other investigators have studied the impact strength or fracture toughness of fiber/metal-matrix composites. It has been found that composite properties as measured by the miniature Izod impact test can correlate closely with composite properties as measured by various ballistic impact tests and it has been concluded that the miniature Izod test is a reasonable screening test for candidate turbine blade and vane materials. Happily, this test is easy to run, gives a numerical result, and requires little material per specimen. Dean indicated that the Charpy impact strengths of unalloyed tungsten/superalloy composites can be a function of test temperature (ref. 2). Tetelmen found that the fracture toughness of composites as measured by tension tests is directly related to the toughness of the fibers and matrix as measured by tension tests (ref. 3); this implied to the present authors that fiber and matrix toughness may be related to impact strength as well.

The current program generated miniature Izod impact strength data for three different tungsten/metal-matrix composites. These data will be presented in subsequent pages and used to describe how certain variables can affect the impact strength of the tested composites. The variables include fiber toughness, matrix toughness, fiber-matrix reaction, fiber content, notches, temperature, heat treatment of the composite, and hot working of the composite. Also, the potential ability of tungsten-alloy/superalloy composites to satisfy turbine blade and vane impact resistance requirements will be evaluated.

Uniaxially reinforced composites were fabricated from continuous lengths of doped unalloyed-tungsten lamp filament wire and three matrix metals - copper, copper-nickel, and a nickel-base superalloy. Their fiber contents ranged from 0 to 70 volume percent. Unnotched and v-notched miniature Izod and standard Charpy impact specimens were impact tested at various temperatures from 297 to 1365 K ($75^{\circ}$ to $2000^{\circ}$ F). The tested specimens were examined using standard optical metallographic and scanning electron microscope techniques. The resulting data were analyzed mathematically and graphically.

## MATERIALS, APPARATUS, AND PROCEDURE

### Wire Material

The wire reinforcement used in this program was commercial, lamp filament, 218CS tungsten having a diameter of 0.038 centimeter (0.015 in.). It was cleaned and straightened after drawing but received no further treatment.

### Matrix Material

Three principle matrices were used in this program, namely OFHC (oxygen-free high conductivity) copper, copper - 10 (weight percent) nickel, and a nickel-base superalloy with a nominal composition of 56 nickel, 25 tungsten, 15 chromium, 2 aluminum, and 2 titanium. In addition to the foregoing, copper - 7 nickel was used for three specimens. The copper was obtained as a 0.63-centimeter (0.25-in.) bar and a 0.089-centimeter (0.035-in.) sheet. The copper-nickel was prepared in helium from OFHC copper and 99.7 percent pure nickel. The nickel alloy had been vacuum cast and subsequently atomized into a fine powder with a particle size range of -325 to +500 mesh; it was part of the lot of material described in reference 1, and was selected for its compatability with tungsten fibers.

The use of three matrices produced desired variations in matrix toughness and fiber-matrix reaction. Copper epitomizes toughness, ductility, and nonreactivity with tungsten fibers. Copper-nickel is also tough and ductile, but it reacts with tungsten fibers to form a brittle recrystallized zone in the perimeter of the fibers (ref. 4). The nickel-base superalloy reacted with tungsten fibers similarly to copper-nickel, but was brittle.

### Composite Fabrication

Uniaxially reinforced, continuous fiber composites were fabricated by two methods. Tungsten/copper and tungsten/copper-nickel composites were made by liquid metal infiltrations, while tungsten/nickel-base superalloy composites were made by powder slipcasting followed by hot isostatic pressing (HIP).

Tungsten/copper and tungsten/copper-nickel composites containing over 20 volume percent fibers were fabricated in vertically oriented mullite tubes that were open at the upper end and closed at the lower end. A cylindrical bundle of fibers was inserted into a tube and then pushed down into the tube until the lower end of the fiber bundle contacted the bottom of the tube. Next a cylindrical bar of copper or copper-nickel was inserted into the tube so that its lower end rested on the upper end of the fiber bundle. Then the tube was placed in a resistance wound furnace and heated to the infiltration temperature where it was held for 1 hour in a vacuum of 0.013 newton per square meter ($1\times10^{-4}$ torr). The infiltration temperatures used for tungsten/copper were either 1480 or 1700 K ($2200^{\circ}$ to $2600^{\circ}$ F), and for tungsten/copper-nickel they were either 1480, 1590, or 1700 K ($2200^{\circ}$, $2400^{\circ}$, or $2600^{\circ}$ F). Cylindrical composite bars measuring 1.9 centimeters in diameter by 5 to 10 centimeters long (0.75 in. by 2 to 4 in.) were obtained.

Tungsten/copper composites containing less than 20 volume percent fibers were fabricated in horizontally oriented zirconia boats (fig. 1). These composites were built up in the boats by alternating layers of tungsten fibers with sheets of OFHC copper to provide a uniform distribution of the fibers. Square stainless steel spacer sheets were placed at each end of the copper sheets. The fiber ends were cemented to these spacers, and the spacers were, in turn, cemented to the boat. The spacers and refractory cement

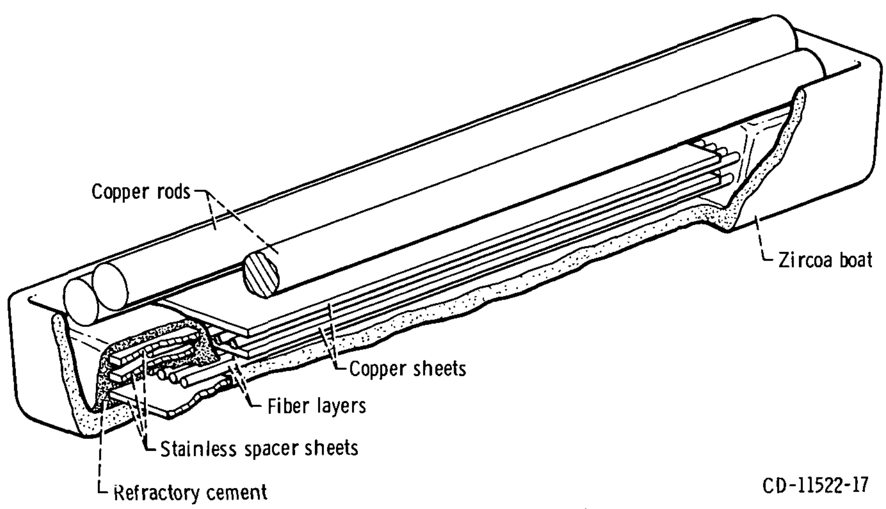



Figure 1. - Cutaway of layup procedure for tungsten/copper composites with fiber contents lower than 20 volume percent.

held the fibers in position during infiltration. To complete the lay up procedure, bars of OFHC copper were placed on top of the final layer of fibers. The assembly was heated to 1480 K (2200° F) in a resistance wound furnace and held at temperature for 1 hour in a vacuum of 0.013 newton per square meter ($1\times10^{-4}$ torr). Rectangular composite bars measuring 1.3 by 1.6 by 9.0 centimeters (0.5 by 0.6 by 3.5 in.) were obtained.

Tungsten/superalloy composites were fabricated by the slip casting process described in reference 1. The slip consisted of a nickel-base superalloy powder suspended in an aqueous solution of an ammonium salt of algenic acid. It was cast about the fibers using the apparatus shown in figure 2. The dried slip-cast composites were sintered in

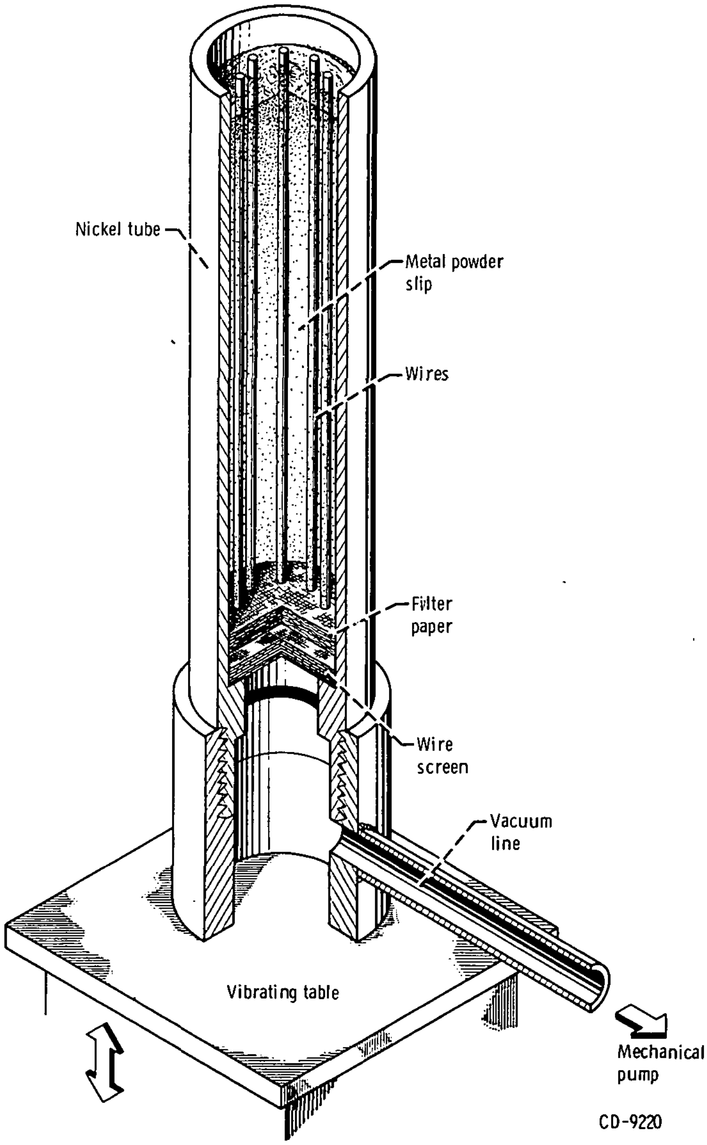



Figure 2. - Slip casting apparatus.

hydrogen at 1090 K (1500° F) to drive off the salt residue and clean the powder of surface oxides. Then, the sintered composites were densified by HIP in helium at 140 meganewtons per square meter for 1 hour at 1090 K (20 000 psi for 1 hr at 1500° F), and then pressed for 1 hour at 1365 K (2000° F). Composite bars of over 99 percent theoretical density were obtained; they had a diameter of either 0.95 or 1.9 centimeters and a length of 10 centimeters (0.375 or 0.75 in. by 4.0 in.).

## Rolling and Thermal Treatment

In an earlier program, the impact strengths of as-HIP tungsten/superalloy composites were found to be poor at 297 K (75° F) (ref. 1). This was attributed primarily to low matrix toughness resulting from weak bonds among the matrix powder particles. Two approaches to strengthening these bonds, and thus improving composite impact strength, were tried in the current program. First, some as-HIP composite bars were round rolled at 1365 K (2000° F) to 78 percent reduction in area. Multiple passes parallel to the fiber direction were used, each pass giving a 5-percent reduction in the previous area. Second, some miniature Izod specimens of as-HIP tungsten/superalloy were heat treated prior to testing. These specimens were heated in high purity helium to 1365 K (2000° F) and held at temperature for 100 or 250 hours.

## Impact Specimen Configuration

Miniature Izod and two Charpy specimens, with fibers parallel to their long dimension, were ground from the previously described composite bars. Some specimens were unnotched, while others were v-notched; all had a surface finish of 4 micrometers (125 $\mu$in.) or better. The miniature Izod specimens were one-half the standard size specified in ASTM specification E-23-66 (Notched Bar Testing of Metallic Materials), whereas the Charpy specimens were the standard size specified in E-23-66. These specimens are shown in figures 3 and 4.

## Impact Testing Machine

A modified, Bell Telephone Laboratory type miniature Izod impact testing machine and a standard size Charpy impact testing machine were used in this program. The Charpy machine was calibrated for 0 to 298 joules (0 to 220 ft-lb) according to ASTM specification E-23-66. The miniature Izod machine was similar in appearance and operation to larger standard Izod machines (fig. 5). However, its gripping fixture had

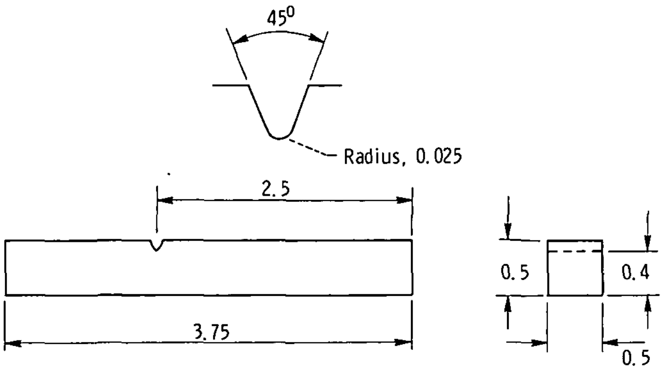



Figure 3. - Miniature Izod impact specimen. Unnotched specimens have the same dimensions as notched specimens but no notch. All dimensions are in centimeters unless otherwise noted.

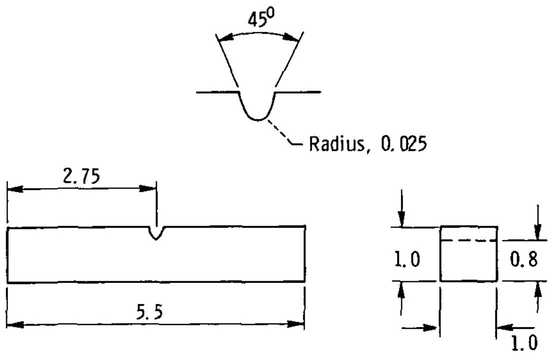



Figure 4. - Charpy impact specimen. Unnotched specimens have the same dimensions as notched specimens but no notch. All dimensions are in centimeters unless otherwise noted.

been modified to allow heating of the specimens while they were clamped in the machine. The modification minimized conductive heat loss by the following means: it reduced the contact area between the grip and the specimen; it reduced the contact area between the grip and the bed of the machine; and it caused some portions of the grip to be thermally insulated from the bed of the machine. In addition, the modification provided for a thermocouple to touch the specimen for the duration of the heat up and test. The thermocouple was located about 0.15 centimeters (0.06 in.) from the specimen cross section where fracture was expected to begin (the cross section even with and parallel to the top surface of the gripping fixture). The same gripping fixture was used for all tests. The miniature Izod machine was calibrated according to ASTM specification E-23-66 for three energy ranges. These were 0 to 3.05 joules, 0 to 7.80 joules, and 0 to 12.9 joules (0 to 27 in.-lb, 0 to 69 in.-lb, and 0 to 114 in.-lb). The tup (striking edge) struck the minia-

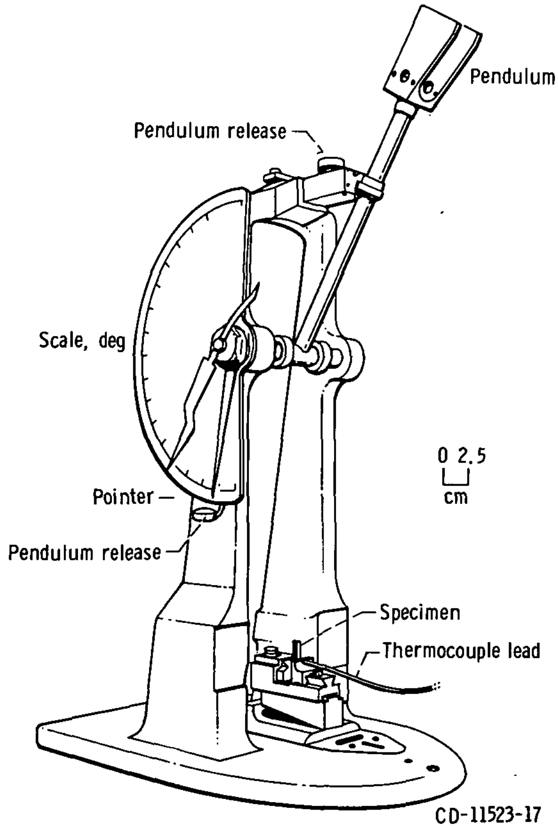


Figure 5. - Miniature Izod impact testing machine.

ture Izod specimens approximately 2.2 centimeters (0.87 in.) from the cross section where fracture began at a speed of 3.48 meters per second (136 in./sec).

## Impact Testing

Miniature Izod specimens were tested from 297 to 1030 K ($75^{\circ}$ to $1400^{\circ}$ F), and two Charpy specimens were tested at 1365 K ($2000^{\circ}$ F).

The miniature Izod specimens were heated, when required, with a hot air blower or multiple propane torches. The hot air blower was used for tests at 365 and 420 K ($200^{\circ}$ and $300^{\circ}$ F), whereas torches were used at 480 K ($400^{\circ}$ F) and above. Temperature was monitored continuously during all of the elevated temperature tests by a thermocouple shielded from direct impingement of the hot air blast or torch flame. The specimens were tested after soaking at temperature for 3 to 5 minutes. It should be noted that the specimens were not heated uniformly along their length at temperatures above 530 K ($500^{\circ}$ F); consequently, the recorded temperatures apply only to a test section about 1.6 centimeters (0.6 in.) long. All failures were near the center of this test section, and taking into account the failure mode of the specimens, the authors do not feel that temperature variations outside the test section affected test results significantly.

The Charpy specimens were heated in argon using a resistance wound furnace. After soaking at temperature (as determined by a thermocouple temporarily attached to the specimen) for 10 minutes, they were transferred to the Charpy machine with heated tongs and tested within 5 seconds per ASTM specification E-23-66.

## Metallography

A number of standard techniques were used to examine failed impact specimens. A scanning electron microscope (SEM) and a sterioscopic microscope were used to examine the fracture surfaces of the specimens. Longitudinal photomicrographs were taken to show the extent of fiber debonding, if any. Photomicrographs of transverse sections near the fracture surface were used to obtain a fiber count which was used to calculate the specimen fiber content; the fiber-matrix reaction zone depths were also measured from these photographs.

# RESULTS

## Impact Strength Values

Copper matrix composites. - The impact strength values obtained for tungsten/copper are listed in table I. For the purposes of this report, impact strength is defined as the energy value obtained in a miniature Izod or Charpy impact test. This definition applies only to specimens that fracture completely through the cross section into two or more distinct pieces. If the specimen bends or does not fracture completely, its impact energy value represents a conservative estimate of its true impact strength because a bent or partly fractured specimen can absorb still more energy by bending further or fracturing.

Tungsten/copper specimens containing over 35 volume percent fibers fractured into two pieces when tested at 297 K ($75^{\circ}$ F), whereas for all but one other combination of fiber content and test temperature the specimens bent but did not fracture completely. At 297 K ($75^{\circ}$ F), the impact strength of specimens containing over 35 volume percent fibers decreased as fiber content was increased (fig. 6). The impact strengths of the notched composites at 36 and 40 volume percent fiber contents were appreciably less than unnotched strengths. But at 67 volume percent, the impact strength of the notched specimen was close to that of the unnotched specimens. The impact strengths of unnotched specimens containing over 35 volume percent fibers were greater than 12.8 joules at

TABLE I. - IMPACT STRENGTH VALUES OF

TUNGSTEN/COPPER COMPOSITES

(a) Unnotched specimens

| Infiltration | | Fibers, vol. % | Impact strength | | Failure |
|---|---|---|---|---|---|
| Temperature, K (°F) | Time, hr | | J | in. -lb | |
| Tested at 297 K (75° F) | | | | | |
| 1480 (2200) | 1 | 0.0 | >6.08 | >53.8 | Bent |
| | | .0 | >6.56 | >58.1 | |
| | | 2.0 | >8.10 | >71.7 | |
| | | 5.0 | >7.80 | >69.0 | |
| | | 7.6 | >8.78 | >77.7 | |
| | | 10.0 | >7.80 | >69.0 | |
| | | 11.0 | >7.80 | >69.0 | |
| | | 13.4 | >8.35 | >73.9 | |
| | | 39.0 | 4.43 | 39.2 | Fracture |
| | | 40.0 | 5.32 | 47.1 | |
| | | 43.0 | 3.43 | 30.4 | |
| | | 43.0 | 4.07 | 36.0 | |
| | | 48.0 | 3.88 | 34.3 | |
| | | 55.0 | 3.56 | 31.5 | |
| | | 60.0 | 3.81 | 33.7 | |
| | | 69.0 | 2.53 | 22.4 | |
| | | 69.0 | 2.35 | 20.8 | |
| Tested at 420 K (300° F) | | | | | |
| 1480 (2200) | 1 | 0.0 | >5.57 | >49.3 | Bent |
| | | .0 | >7.26 | >64.3 | |
| | | 1.5 | >7.98 | >70.6 | |
| | | 7.8 | >10.71 | >94.8 | |
| | | 45.0 | >12.88 | >114.0 | |
| | | 56.0 | ------ | ------ | |
| | | 72.0 | ------ | ------ | |
| Tested at 810 K (1000° F) | | | | | |
| 1480 (2200) | 1 | 54.6 | >12.88 | >114.0 | Bent |
| Tested at 297 K (75° F) | | | | | |
| 1700 (2600) | 1 | 32.5 | 4.36 | 38.6 | Fracture |
| Tested at 810 K (1000° F) | | | | | |
| 1700 (2600) | 1 | 38.3 | 11.30 | 100.0 | Fracture |

(b) Notched specimens

| Infiltration | | Fibers, vol. % | Impact strength | | Failure |
|---|---|---|---|---|---|
| Temperature, K (°F) | Time, hr | | J | in. -lb | |
| Tested at 297 K (75° F) | | | | | |
| 1480 (2200) | 1 | 0.0 | >5.69 | >50.4 | Bent |
| | | 36.0 | 3.14 | 27.8 | Fracture |
| | | 41.0 | 2.99 | 26.5 | Fracture |
| | | 67.0 | 2.21 | 19.6 | Fracture |
| Tested at 420 K (300° F) | | | | | |
| 1480 (2200) | 1 | 56.0 | 11.52 | 102.0 | Fracture |

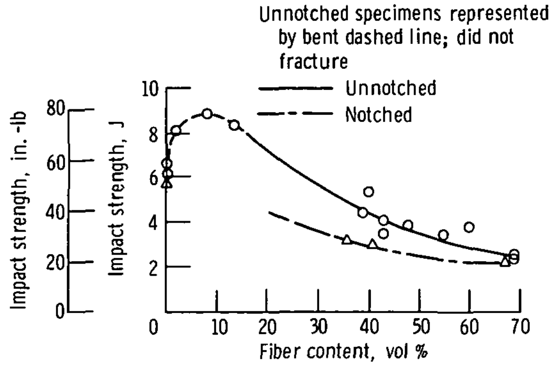



Figure 6. - Room temperature impact strength of tungsten/ copper composites as function of fiber content.

420 K (114 in. -lb at 300° F) and above. These strengths were much higher than those obtained at 297 K (75° F). The lone notched specimen tested at 420 K (300° F) fractured; its fiber content was 56 volume percent, and its impact strength was 11.52 joules (102 in. -lb).

Copper-nickel matrix composites. - The impact strength values obtained for tungsten/copper-nickel are listed in table II. These composites were fabricated to show the effect of fiber-matrix reaction on impact strength. The reaction zone depth was varied principally by varying the infiltration temperature - higher temperatures gave greater depth. Figure 7 shows that as reaction (recrystallization) zone depth increases, the impact strength of the composite decreases, if only slightly, at all test temperatures. The figure also shows that the impact strengths of composites containing fibers with 0.0 and 0.0028 centimeter (0.0011 in.) reaction zone depths (copper - 7 nickel and copper - 10 nickel, respectively) tend to increase with increasing temperature. But the impact strengths of composites containing fibers with reaction zone depths greater than 0.0103 centimeter (0.0041 in.) (copper - 10 nickel) do not increase with increasing temperature over the range of test temperatures used. Comparing the impact strengths in table I with those in table II reveals that the impact strengths of the tungsten/copper composites are greater than those of the tungsten/copper - 10 nickel composites, but the impact strengths of the unreinforced matrices are about the same. Furthermore, tungsten/copper and tungsten/copper - 7 nickel, neither of which exhibited visible fiber-matrix reaction, had equivalent impact strengths.

As-HIP superalloy matrix composites. - The impact strength values obtained for as-HIP tungsten/superalloy are listed in table III. In general, impact strength decreased with increasing fiber content at temperatures below 530 K (500° F) but increased with increasing fiber content above 530 K (500° F) (fig. 8). Figure 9 is a cross-plot of impact strength as a function of temperature. Note the sharp increase in impact strength at 530 K (500° F) for the 60 volume percent unnotched composite; also, note that the unre-

TABLE II. - IMPACT STRENGTH VALUES OF

TUNGSTEN/COPPER-NICKEL COMPOSITES

(a) Copper - 7 nickel matrix

| Tested at | | Fibers, vol. % | Impact strength | | Failure |
|---|---|---|---|---|---|
| K | $^{o}F$ | | J | in. -lb | |
| Infiltrated at 1480 K (2200° F), 1 hr unnotched | | | | | |
| 297 | 75 | 55.0 | 3.16 | 28.0 | Fracture |
| 420 | 300 | 61.0 | >12.88 | >114.0 | Bent |
| 810 | 1000 | 55.3 | >12.88 | >114.0 | Bent |

(b) Copper - 10 nickel matrix

| Tested at | | Fibers, vol. % | Impact strength | | Failure |
|---|---|---|---|---|---|
| K | $^{o}F$ | | J | in. -lb | |
| Infiltrated at 1480 K (2200° F), 1 hr unnotched | | | | | |
| 297 | 75 | 0.0 | >6.21 | >55.0 | Bent |
| 297 | 75 | 53.5 | 2.32 | 20.5 | Fracture |
| 420 | 300 | 55.7 | 1.76 | 15.6 | Fracture |
| 530 | 500 | 53.5 | 1.92 | 17.0 | Fracture |
| 810 | 1000 | 56.2 | >12.88 | >114.0 | Bent |
| Infiltrated at 1480 K (2200° F), 1 hr notched | | | | | |
| 297 | 75 | 0.0 | >5.71 | >50.5 | Bent |
| 297 | 75 | 55.2 | 2.04 | 18.1 | Fracture |
| Infiltrated at 1590 K (2400° F), 1 hr unnotched | | | | | |
| 297 | 75 | 51.3 | 2.32 | 20.5 | Fracture |
| 420 | 300 | 49.5 | 2.12 | 18.8 | Fracture |
| 810 | 1000 | 49.6 | 2.12 | 18.8 | Fracture |
| Infiltrated at 1700 K (2600° F), 1 hr unnotched | | | | | |
| 297 | 75 | 56.7 | 1.64 | 14.5 | Fracture |
| 810 | 1000 | 59.4 | 1.43 | 12.7 | Fracture |

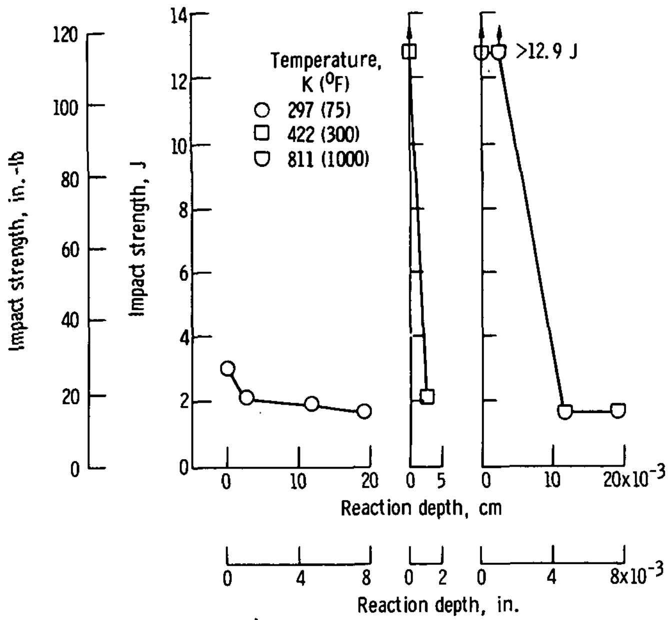
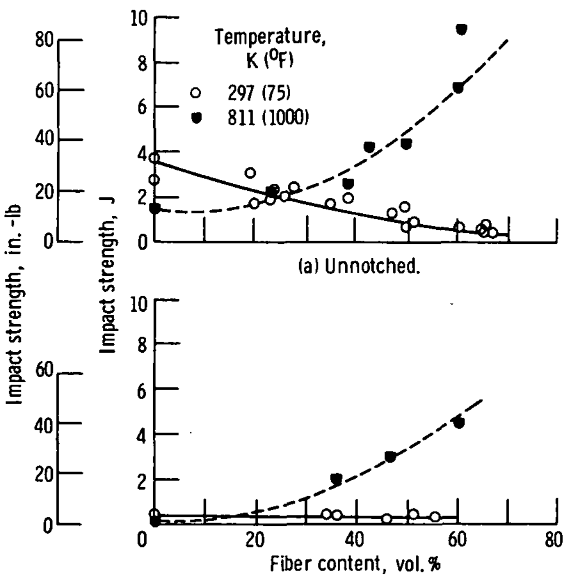



Figure 7. - Impact strength of unnotched tungsten/copper-nickel as function of fiber-matrix reaction zone depth, approximately 55 volume percent fibers. Fiber diameter, 0.038 centimeter.




(b) Notched.

Figure 8. - Impact strength of unnotched and notched as-HIP tungsten/superalloy as a function of fiber content.

TABLE III. - IMPACT STRENGTH VALUES OF AS-HIP TUNGSTEN/SUPERALLOY COMPOSITES

(a) Unnotched

| Fibers, vol. % | Impact strength | | Failure |
|---|---|---|---|
| | J | in. -lb | |
| Tested at 297 K (75° F) | | | |
| 0.0 | 3.65 | 32.3 | Fracture |
| .0 | 3.69 | 32.7 | |
| .0 | 2.78 | 24.6 | |
| 19.0 | 3.07 | 27.2 | |
| 20.0 | 1.77 | 15.7 | |
| 23.3 | 1.88 | 16.6 | |
| 23.6 | 2.35 | 20.8 | |
| 26.0 | 2.08 | 18.4 | |
| 27.8 | 2.43 | 21.5 | |
| 35.0 | 1.71 | 15.1 | |
| 38.4 | 1.94 | 17.2 | |
| 38.4 | 1.94 | 17.2 | |
| 47.0 | 1.36 | 12.0 | |
| 49.7 | 1.60 | 14.2 | |
| 49.7 | .72 | 6.4 | |
| 51.3 | .93 | 8.2 | |
| 60.4 | .72 | 6.3 | |
| 64.7 | .60 | 5.3 | |
| 65.0 | .38 | 3.4 | |
| 65.7 | .79 | 7.0 | |
| 67.0 | .44 | 3.9 | |
| Tested at 365 K (200° F) | | | |
| 20.5 | 2.68 | 23.7 | Fracture |
| 25.4 | 1.55 | 13.7 | Fracture |
| 57.2 | .79 | 7.0 | Fracture |
| 62.4 | .46 | 4.1 | Fracture |
| Tested at 420 K (300° F) | | | |
| 0.0 | 2.43 | 21.5 | Fracture |
| .0 | 2.91 | 25.8 | |
| 18.2 | 3.28 | 29.0 | |
| 38.0 | 1.76 | 15.6 | |
| 48.8 | 2.08 | 18.4 | |
| 50.0 | .89 | 7.9 | |
| 56.0 | 1.12 | 9.9 | |
| 57.0 | .73 | 6.5 | |
| 66.0 | .89 | 7.9 | |
| Tested at 480 K (400° F) | | | |
| 58.8 | 1.29 | 11.4 | Fracture |
| 57.9 | 1.24 | 11.0 | Fracture |
| 59.3 | 1.29 | 11.4 | Fracture |
| Tested at 530 K (500° F) | | | |
| 62.8 | 4.12 | 36.5 | Fracture |
| Tested at 645 K (700° F) | | | |
| 60.6 | 8.21 | 72.7 | Fracture |
| Tested at 810 K (1000° F) | | | |
| 0.0 | 1.42 | 12.6 | Fracture |
| 23.4 | 2.23 | 19.7 | |
| 38.5 | 2.59 | 22.9 | |
| 42.3 | 4.24 | 37.5 | |
| 49.8 | 4.47 | 39.6 | |
| 60.0 | 6.90 | 61.1 | |
| 60.6 | 9.54 | 84.4 | |
| Tested at 1030 K (1400° F) | | | |
| 54.7 | 5.32 | 47.1 | Fracture |
| Tested at 1365 K (2000° F) | | | |
| 58.1 | 39.3 | 348.0 | Charpy |

(b) Notched

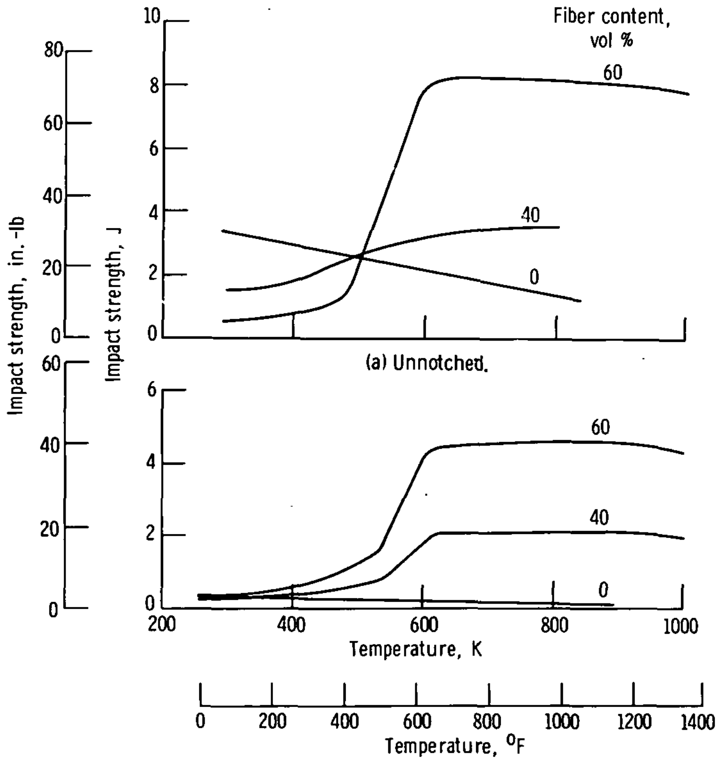
| Fibers, vol. % | Impact strength | | Failure |
|---|---|---|---|
| | J | in. -lb | |
| Tested at 297 K (975° F) | | | |
| 0.0 | 0.36 | 3.2 | Fracture |
| .0 | .38 | 3.4 | |
| 34.3 | .41 | 3.6 | |
| 35.2 | .18 | 1.6 | |
| 36.4 | .36 | 3.2 | |
| 46.0 | .25 | 2.2 | |
| 51.3 | .42 | 3.7 | |
| 55.4 | .28 | 2.5 | |
| Tested at 365 K (200° F) | | | |
| 47.1 | 0.36 | 3.2 | Fracture |
| 51.0 | .34 | 3.0 | Fracture |
| Tested at 420 K (300° F) | | | |
| 0.0 | 0.34 | 3.0 | Fracture |
| .0 | .38 | 3.4 | |
| 25.0 | .50 | 4.4 | |
| 35.8 | .49 | 4.3 | |
| 36.3 | .36 | 3.2 | |
| 48.0 | .71 | 6.3 | |
| 49.7 | .49 | 4.3 | |
| 50.0 | .89 | 7.9 | |
| 56.0 | .73 | 6.5 | |
| 57.0 | 1.12 | 9.9 | |
| 66.0 | .89 | 7.9 | |
| Tested at 530 K (500° F) | | | |
| 54.7 | 1.34 | 11.9 | Fracture |
| Tested at 645 K (600° F) | | | |
| 39.0 | 2.23 | 19.7 | Fracture |
| Tested at 645 K (700° F) | | | |
| 53.0 | 3.14 | 27.8 | Fracture |
| Tested at 810 K (1000° F) | | | |
| 0.0 | 0.28 | 2.5 | Fracture |
| 36.9 | 2.02 | 17.9 | Fracture |
| 46.6 | 2.97 | 26.3 | Fracture |
| 60.1 | 4.47 | 39.6 | Fracture |
| Tested at 1030 K (1400° F) | | | |
| 60.6 | 4.24 | 39.6 | Fracture |
| Tested at 1365 K (2000° F) | | | |
| 60.0 | 37.3 | 330.0 | Charpy |

inforced matrix loses impact strength at higher temperatures. The notched specimens behaved similarly to the unnotched specimens as seen by comparing figures 8 and 9; however, their impact strengths were much lower.

Heat-treated and hot-worked superalloy matrix composites. - Heat treatment or hot working improved the impact strength of as-HIP tungsten/superalloy; these results are summarized in table IV. Heat treatment nearly doubled the 297 K (75° F) impact strength of a 45 volume percent composite and increased the impact strength of the notched unreinforced matrix by almost four times. Round rolling increased the 297 K (75° F) impact strength of a 56 volume percent composite by nearly four times. The impact strengths of the notched and unnotched rolled specimens were similar.

## Metallography

Fiber-matrix reaction zone depths. - The fiber-matrix reaction zone depths measured for the composites tested in this program are listed in table V. The copper matrix did not react with the tungsten fibers during infiltration at 1480 K (2200° F) because



(b) Notched.

Figure 9. - Impact strength of unnotched and notched as-HIP tungsten/superalloy as function of temperature and various fiber contents.

TABLE IV. - IMPACT STRENGTH VALUES OF HOT-WORKED OR HEAT-TREATED TUNGSTEN/SUPERALLOY AT 297 K ($75^\circ$ F)

| Fibers, vol. % | Impact strength | | Notch |
|---|---|---|---|
| | J | in.-lb | |
| Round rolled at 1365 K ($2000^\circ$ F) | | | |
| 54.0 | 3.29 | 29.1 | No |
| 58.0 | 3.51 | 31.1 | Yes |
| Heat treated at 1365 K ($2000^\circ$ F), 100 hr | | | |
| 41.9 | 2.46 | 21.8 | No |
| 47.7 | 2.28 | 20.2 | No |
| 66.0 | 1.11 | 9.8 | No |
| 71.0 | .99 | 8.8 | No |
| Heat treated at 1365 K ($2000^\circ$ F), 250 hr | | | |
| 0.0 | 1.32 | 11.7 | Yes |
| 45.0 | 2.50 | 22.1 | No |
| 68.0 | .75 | 6.6 | No |
| 70.0 | .75 | 6.6 | No |

TABLE V. - FIBER-MATRIX REACTION RECRYSTALLIZATION ZONE DEPTHS FOR AS-FABRICATED 218CS-TUNGSTEN/ METAL-MATRIX COMPOSITES

[Fabrication time at temperature, 1 hr.]

| Matrix | Fabrication temperature, K ($^\circ$F) | Zone depth | |
|---|---|---|---|
| | | cm | in. |
| Copper | 1480 (2200) | 0.0 | 0.0 |
| Copper | 1700 (2600) | .0190 | .0075 |
| Copper - 7 nickel | 1480 (2200) | .0 | .0 |
| Copper - 10 nickel | 1480 (2200) | .0028 | .0011 |
| Copper - 10 nickel | 1590 (2400) | .0103 | .0041 |
| Copper - 10 nickel | 1700 (2600) | .0190 | .0075 |
| Nickel-base superalloy | 1365 (2000) | .0019 | .0007 |

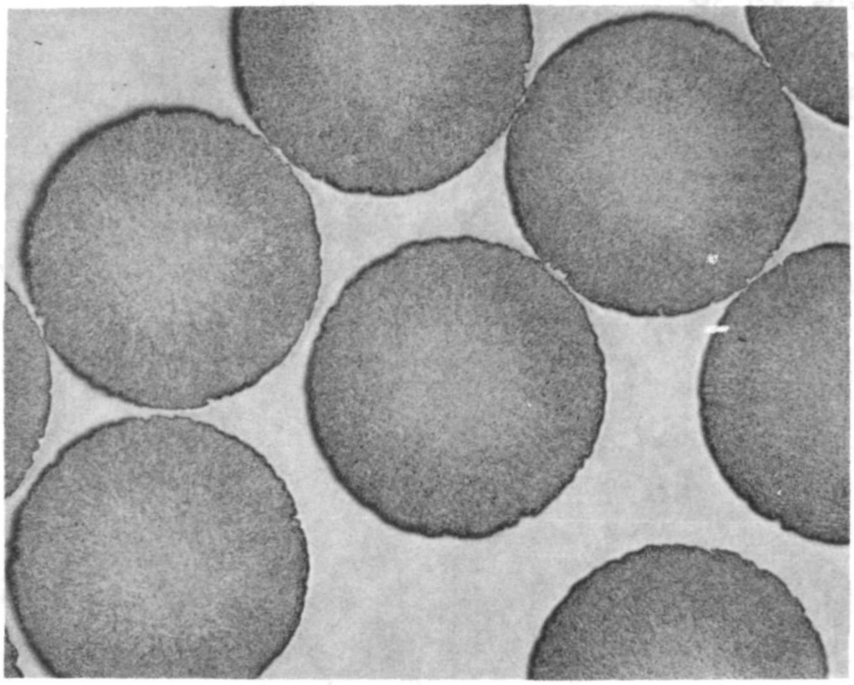
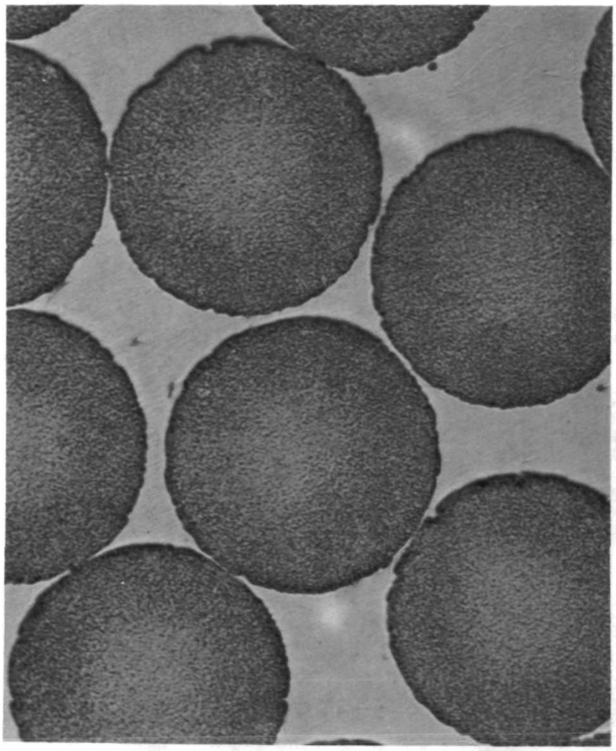


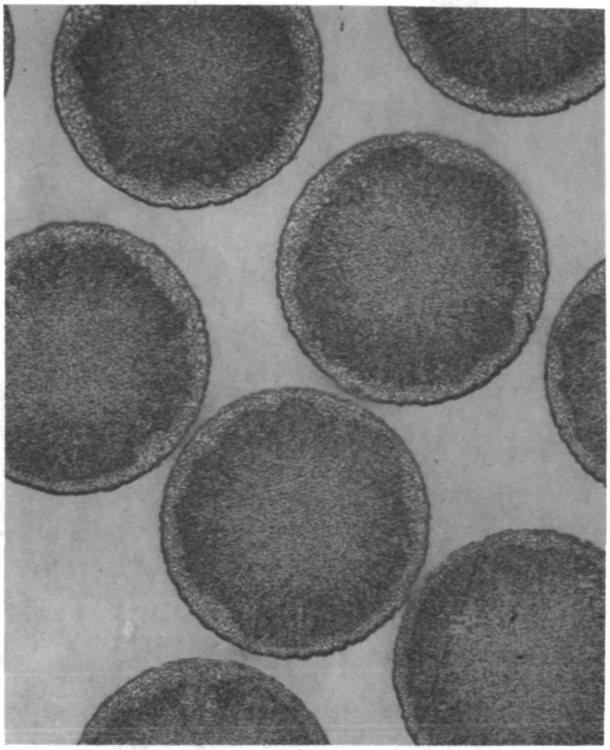
Figure 10. - As-infiltrated tungsten/copper cross section. X100.

copper and tungsten are mutually insoluble (fig. 10). The copper - 10 nickel matrix reacted with the tungsten fibers to form a recrystallized zone in the perimeter of the fibers (fig. 11). In an earlier program, a similar zone was attributed to penetration of nickel into the tungsten fibers (ref. 4). The zone depths measured in the current investigation increased as the infiltration temperature was raised to 1590 K (2400° F), as shown in table V. Note, however, that thermal annealing, rather than diffusion penetration, was responsible for much of the recrystallization in composites infiltrated at 1700 K (2600° F). A few tungsten/copper - 7 nickel composites were fabricated at 1480 K (2200° F) for 1 hour; there was no visible reaction in these specimens (a similar phenomenon was noted in ref. 4). The nickel-base superalloy matrix reacted with the tungsten fibers at 1365 K (2000° F) to form a recrystallized zone similar in appearance to that caused by the copper - 10 nickel matrix at 1480 K (2200° F) (figs. 11(b) and 12).

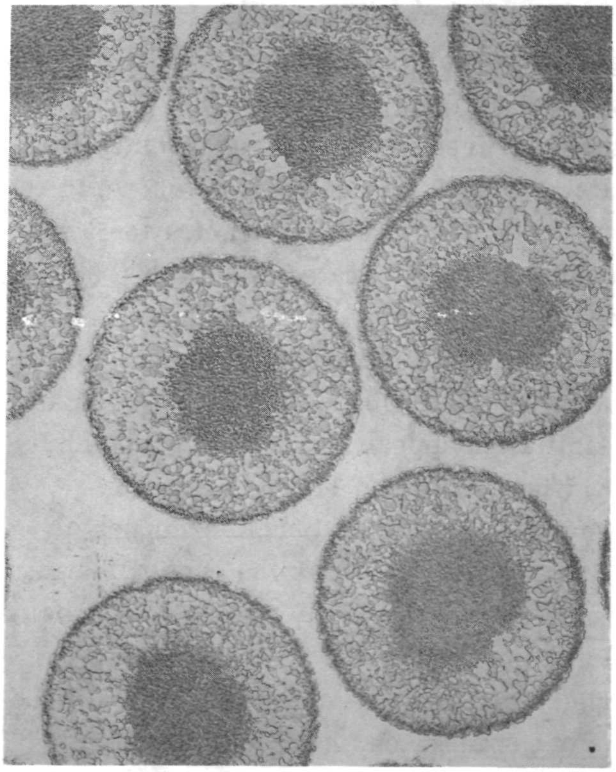
Appearance of impact specimen fracture surface. - In tests of tungsten/copper at 297 K (75° F), the tungsten fibers failed in a brittle manner, whereas the copper matrix failed ductily by necking on a microscopic scale and debonded slightly from the fibers (fig. 13). The striations on the matrix (fig. 13) are impressions of the drawing die marks on the surface of the tungsten fibers; tungsten and copper form a mechanical bond which is made stronger by the surface roughness of the tungsten fibers. As implied by figure 14, the tungsten/copper impact specimens bent at all test temperatures other than 297 K (75° F), so no fracture surface studies were possible. The fracture surfaces of



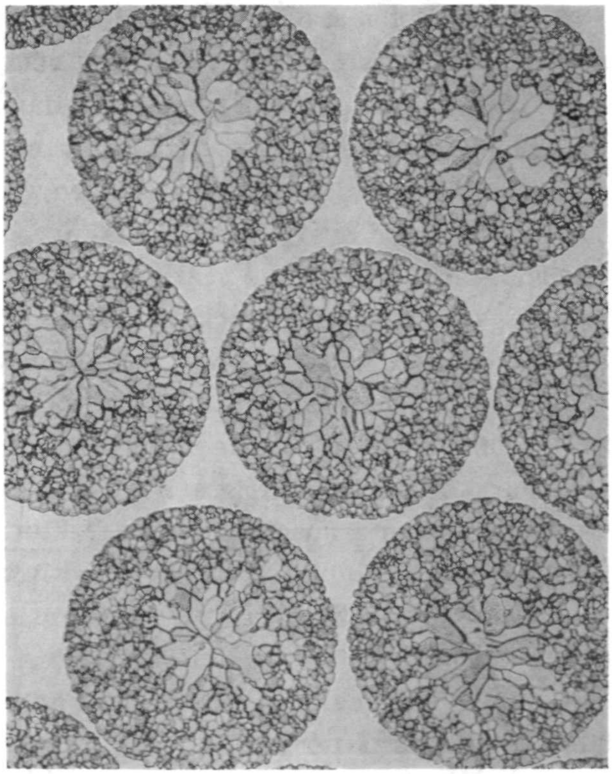
(a) Copper - 7 nickel; 1 hour at 1480 K.



(b) Copper - 10 nickel; 1 hour at 1480 K.



(c) Copper - 10 nickel; 1 hour at 1590 K.



(d) Copper - 10 nickel; 1 hour at 1700 K.

Figure 11. - As-infiltrated tungsten/copper-nickel cross sections. Note that changing infiltration temperature and matrix nickel content affects recrystallization zone depth. X100.

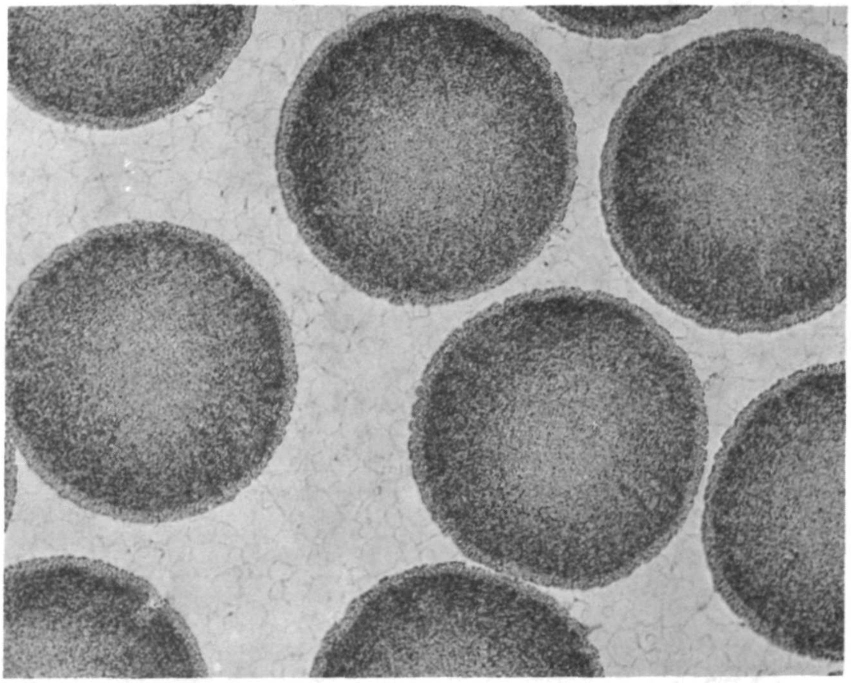
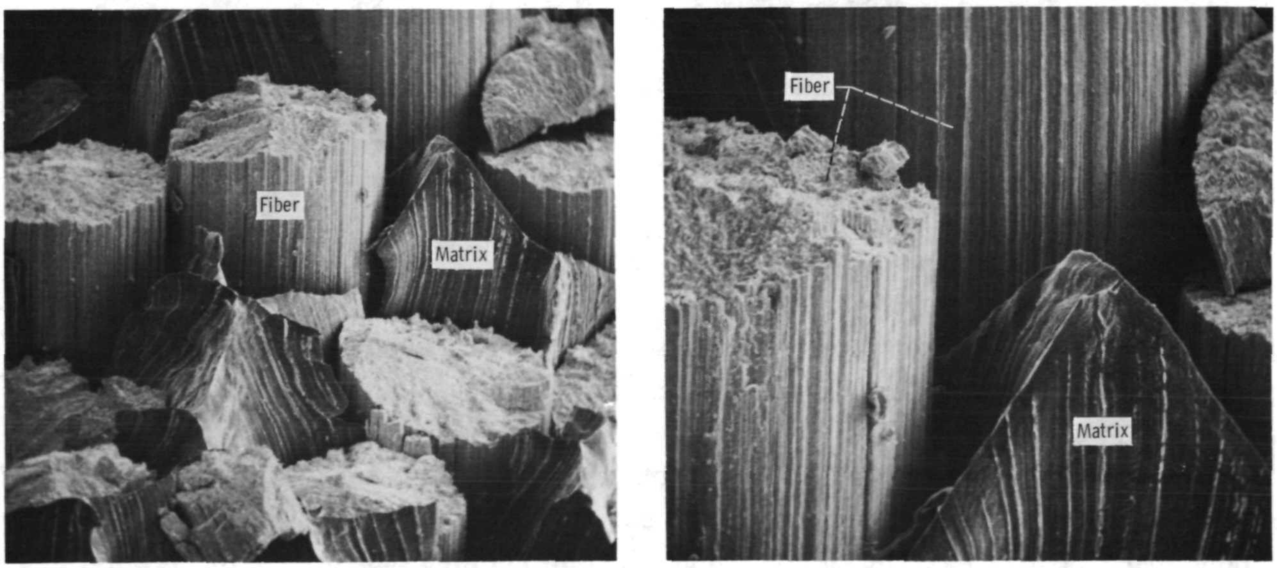


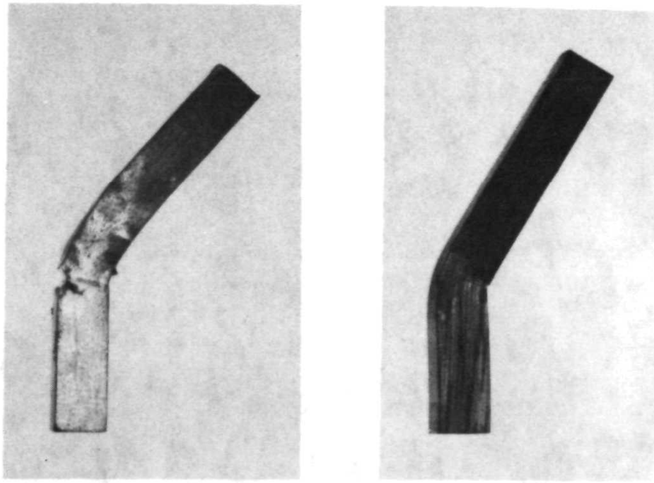
Figure 12. - As-HIP tungsten/nickel-base superalloy cross section. X100.




(a) X100.

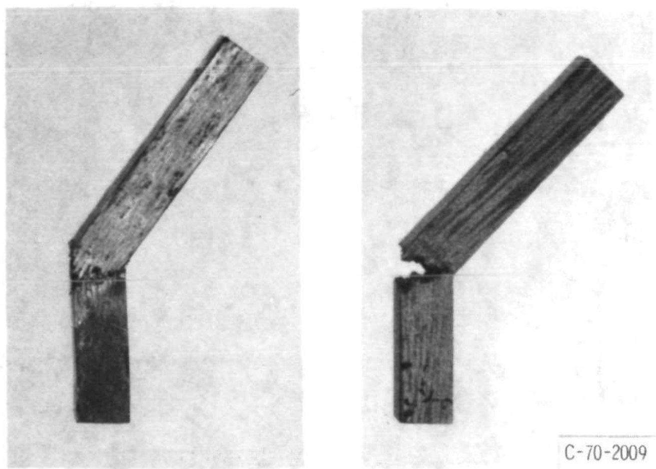
(b) X250.

Figure 13. - Fracture surface of tungsten/copper tested at 297 K.



(a) Copper matrix: notched; 0 volume percent; 297 K.

(b) Copper - 10 nickel matrix: unnotched; 56 volume percent; 810 K.



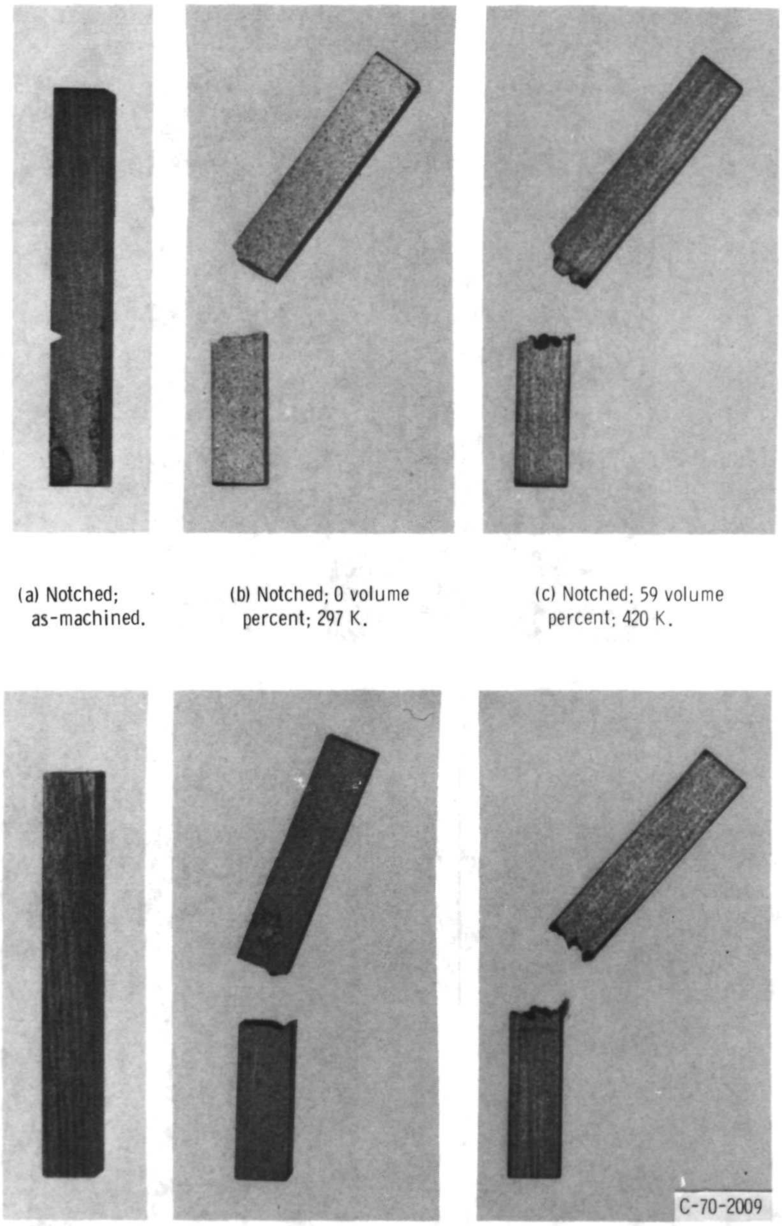

(c) Copper matrix: unnotched; 66 volume percent; 297 K.

(d) Copper - 10 nickel matrix: unnotched; 54 volume percent; 530 K.

Figure 14. - The appearance of typical tungsten/copper and tungsten/copper - 10 nickel impact specimens after testing at various temperatures.

tungsten/copper - 10 nickel were similar in appearance to those of tungsten/copper; the only differences being that necking of the matrix was reduced and debonding was almost nil.

The macroscopic appearance of failed tungsten/superalloy impact specimens indicated brittleness (e.g., fig. 15), and at temperatures below 530 K ($500^{\circ}$ F) the microscopic appearance of both the fibers and as-HIP matrix also indicated brittleness. Nonetheless, in some cases the fibers or matrix did exhibit ductility. As shown in figures 16(a) and 17, below 530 K ($500^{\circ}$ F) the fibers failed in the same plane as the fracture surface with no evidence of ductility or debonding, and the as-HIP matrix parted

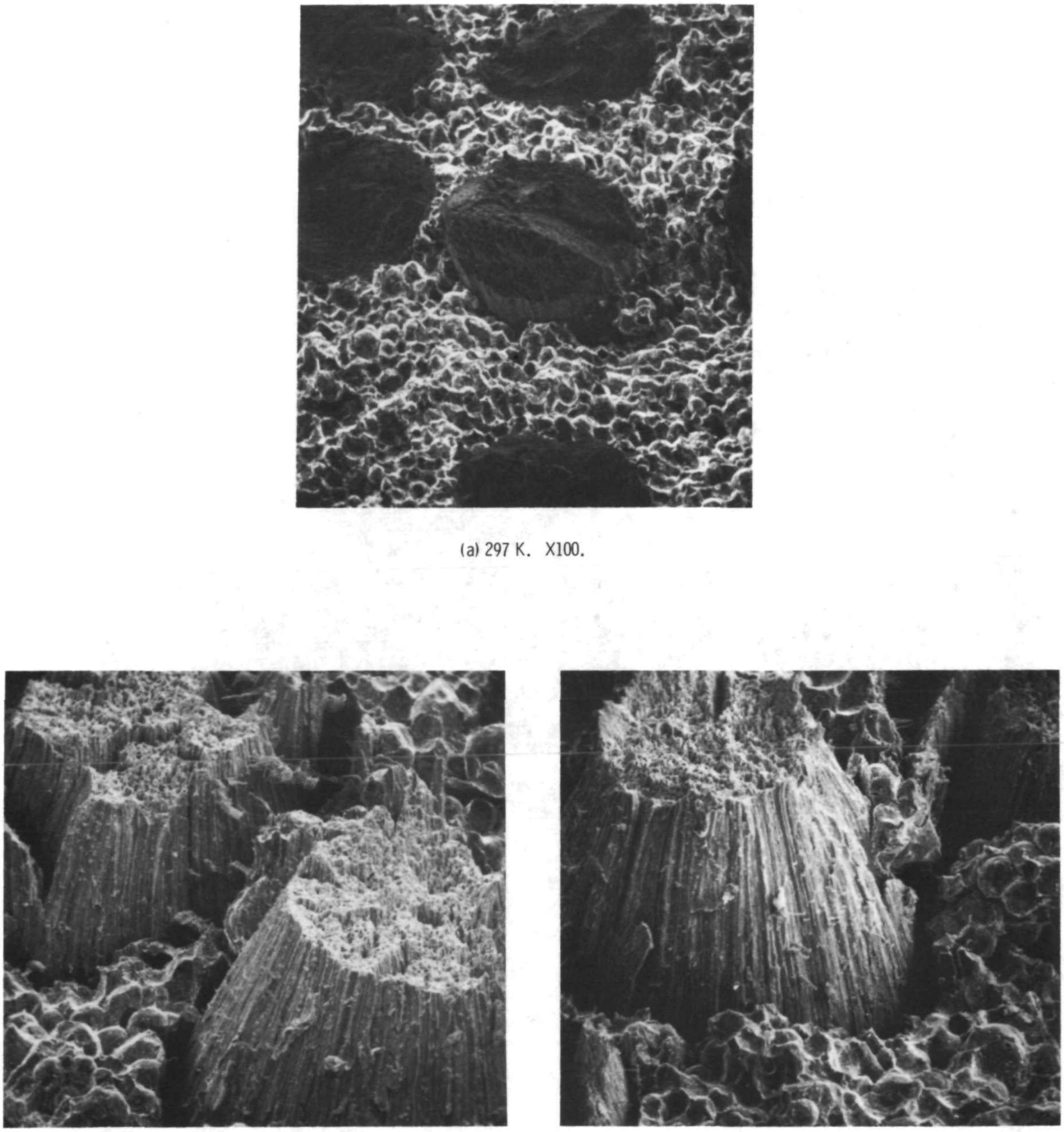



(a) Notched; as-machined.
(b) Notched; 0 volume percent; 297 K.
(c) Notched; 59 volume percent; 420 K.

(d) Unnotched; as-machined.
(e) Unnotched; 0 volume percent; 297 K.
(f) Unnotched; 64 volume percent; 810 K.

Figure 15. - The appearance of typical tungsten/nickel-base superalloy impact specimens before and after testing at various temperatures.

along the original interfaces of the powder particles compacted to form it. On the other hand, figures 16(b) and (c), 18, and 19 show that above 530 K ($500^{\circ}$ F) the fibers fail ductily by necking much as would a fiber tension specimen. The fibers shown in these figures were located near the side of the specimen where fracture initiated (side struck by the tup); the fibers located on the opposite side of the specimen sheared (photographs not available). The fibers in the notched specimens exhibited slightly less ductility than those in unnotched specimens, but even those fibers cut by the notch showed some plastic deformation above 530 K ($500^{\circ}$ F) (fig. 19).



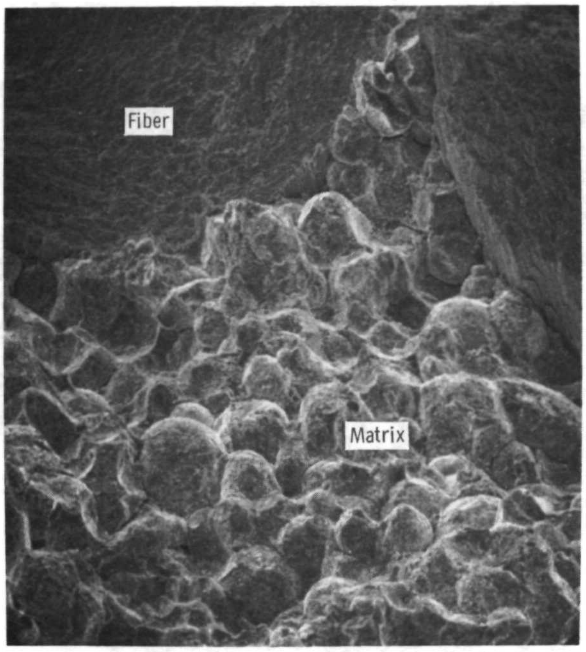
(a) 297 K. X100.

(b) 645 K. X250.

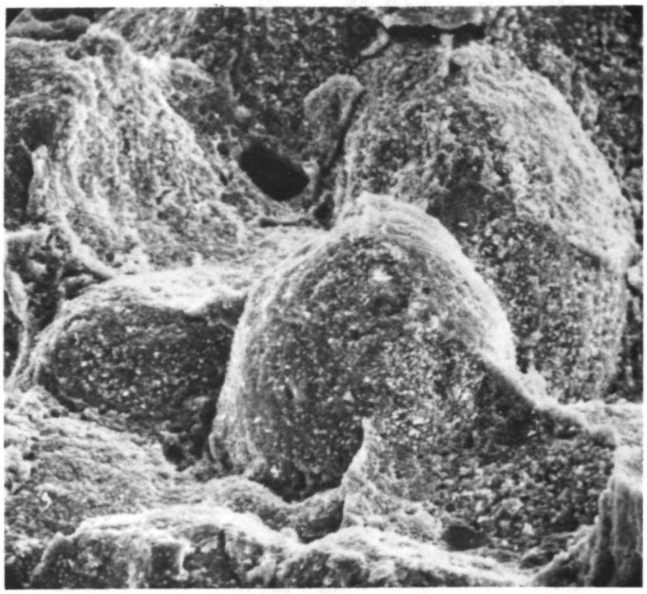
(c) 810 K. X250.

Figure 16. - Typical fracture surface appearance of unnotched as-HIP tungsten/nickel-base superalloy tested at various temperatures.

Heat treatment and round rolling did not change the appearance of the fractured fibers in specimens tested at 297 K (75° F), but they did change the appearance of the matrix. As shown in figure 20, the surface condition of the particle interfaces in the heat-treated matrix suggest an improved bond, with some plastic deformation and tearing at the interfaces. Round rolling changed the structure to the extent that failure proceeded through the particles rather than along their interfaces (fig. 21).




(a) X250.



(b) X1500.

Figure 17. - Fracture surface of as-HIP tungsten/nickel-base superalloy tested at 297 K. Note that powder particles comprising the matrix have separated along their mutual interfaces.

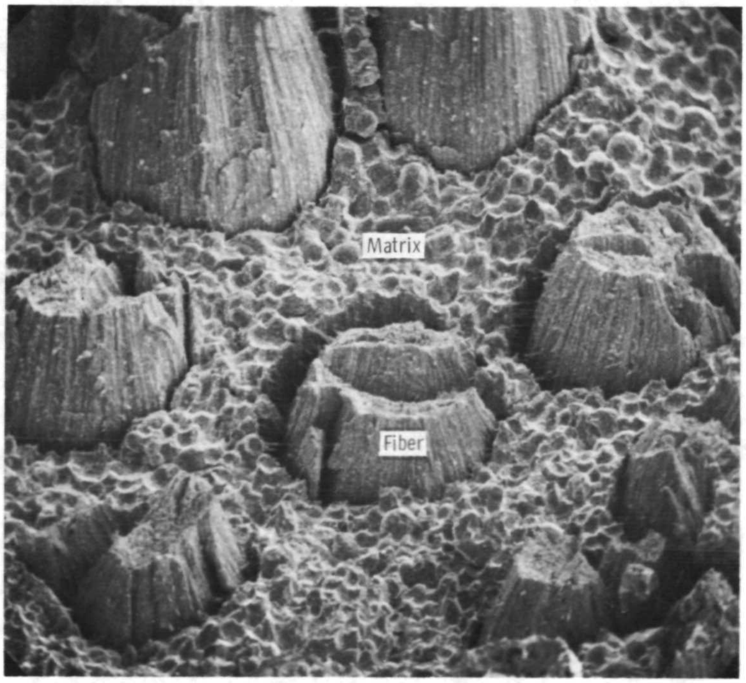
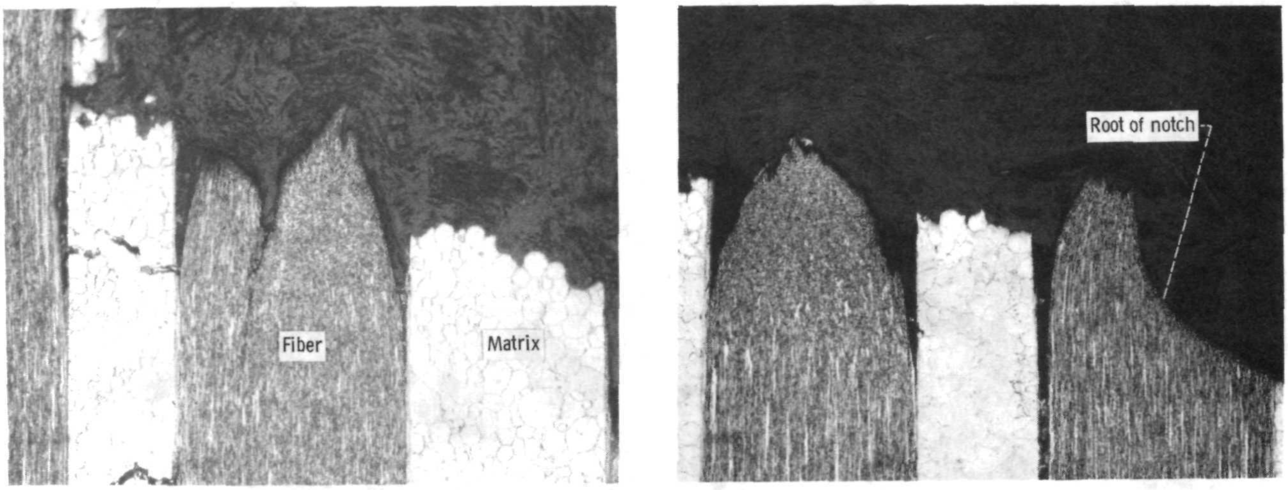
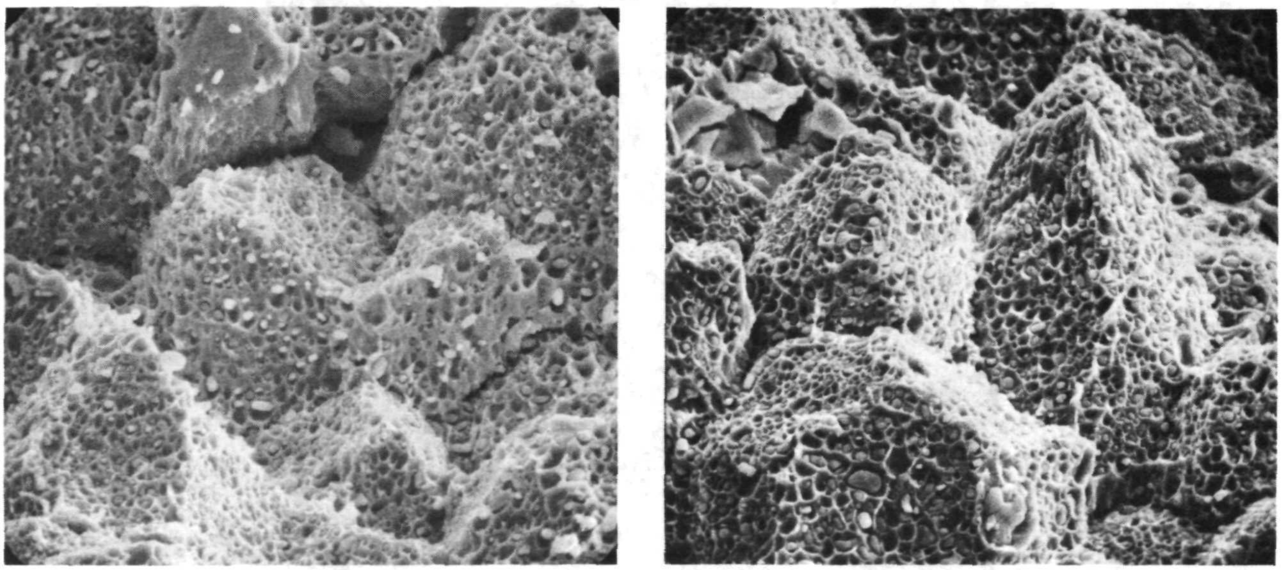



Figure 18. - Fracture surface of notched as-HIP tungsten/nickel-base superalloy tested at 810 K. X100.




(a) 530 K. (b) 810 K.

Figure 19. - Longitudinal sections of notched as-HIP tungsten/nickel-base superalloy. Note that tungsten fibers failed ductility even where cut by notch. X100.



(a) Annealed for 100 hours at 1365 K. (b) Annealed for 250 hours at 1365 K.

Figure 20. - Fracture surfaces of heat treated tungsten/nickel-base superalloy tested at 297 K. X1500.

Figure 21. - Fracture surface of a tungsten/nickel-base superalloy that had been hot rolled to 78 percent reduction in area. Only the matrix is visible in the photograph. X1500.

## DISCUSSION

It has been possible by studying the impact behavior of tungsten fibers combined with three different types of matrixes to obtain a better understanding of variables that can affect the impact strength of metal matrix composites. It will be shown that, for some composites, impact strength can be related to properties of the fibers and matrix and to the volume fraction of fibers. In addition, evidence will be presented which indicates that tungsten/superalloy composites can be made with adequate impact damage resistance to permit their use as turbine blade or vane materials.

### Tungsten/Copper and Tungsten/Copper-Nickel Composites

Tungsten/copper is a ductile matrix composite in which the fibers are brittle below their DBTT (ductile-brittle transition temperature) and ductile above their DBTT. Because of the mutual insolubility of tungsten and copper, there is no fiber-matrix reaction, and the bond between fiber and matrix is mechanical. Since tungsten/copper is a relatively simple system, it was chosen as the basic fiber/matrix model for this program. Adding 7 to 10 percent nickel to the copper does not greatly alter the strength or ductility of the copper; however, the copper - 10 nickel reacts with the tungsten fiber to form a recrystallized zone in the fiber, and a chemical bond is formed between the copper - 10 nickel and tungsten.

Apparently the impact strength of the tungsten/copper is primarily the energy absorbed during elastic-plastic deformation of the fibers and matrix. The reasoning behind this conclusion is as follows. At 297 K ($75^{\circ}$ F) the impact strength of the tungsten/copper declined rapidly as the fiber content was increased from 39 volume percent to over 60 volume percent (fig. 6). This is the behavior one would expect if the impact strength of the composite were primarily the energy absorbed during elastic-plastic deformation of the fibers and matrix because the tungsten fibers were brittle (below their DBTT), and adding them reduced the overall ability of the composite to plastically deform. On the other hand, if the impact strength were due primarily to debonding of the matrix from the fibers, then impact strength would have been expected to increase as fiber content increased because the area available for debonding would have increased. Furthermore, if both debonding and deformation were important, then as fiber content increased, the trade-off between subtracting the effect of the ductile phase (copper) and increasing the total area available for debonding should have resulted in a relatively shallow slope in the impact strength as a function of fiber content curve.

There was some debonding of the matrix from the fibers in the 297 K ($75^{\circ}$ F) tests of tungsten/copper. To assess the effect of this debonding on composite impact strength, it would be instructive to compare the impact strength of tungsten/copper with that of tungsten/copper - 10 nickel, which exhibited no debonding. By comparing the data in tables I and II, one can see that the impact strength of 60 volume percent tungsten/copper is greater than that of 60 volume percent tungsten/copper - 10 nickel by about 1.1 joules (10 in. -lb). This difference in impact strength is related to debonding and not a difference in matrix or fiber properties as is evident in the light of the following observations. First, because the copper - 10 nickel contains a small amount of nickel, its strength and ductility should be nearly that of pure copper. Furthermore, both matrices have similar unreinforced impact strengths. Therefore, the difference in composite impact strengths is probably not due to a difference in matrix strength or ductility. Second, the tungsten fibers in both composites were from the same lot of material, the only dissimilarity being that the fibers in copper - 10 nickel were recrystallized around their perimeter as a result of fiber-matrix reaction. But, tungsten/copper composites with fully recrystallized fibers (infiltrated at 1700 K ($2600^{\circ}$ F)) had nearly the same impact strength at 297 K ($75^{\circ}$ F) as tungsten/copper with unrecrystallized fibers. Therefore, the slight recrystallization mentioned previously should not be responsible for the large difference in composite impact strength. Since fiber and matrix property differences have been ruled out as direct causes of the impact strength difference, it would seem that the difference must be related to debonding. Tungsten and pure copper form a relatively weak mechanical bond, and debonding in tungsten/copper was not too extensive in a longitudinal direction;

hence, the energy absorbed directly by fiber pull out and fiber-matrix separation was probably not the main source of the impact strength difference. Rather, it is felt that debonding in the tungsten/copper specimens relieved constraints on the matrix and thus allowed it to deform plastically to a greater extent than in tungsten/copper - 10 nickel. The energy absorbed during the additional plastic deformation of the pure copper matrix is most likely the major source of the difference in impact strengths.

One of the more interesting features of tungsten/copper concerns its notch sensitivity. For purposes of this report, a material is defined to be notch sensitive at a given temperature when the ratio of its notched impact strength per unit area to its unnotched impact strength per unit area is less than an arbitrary value of 0.9. This ratio may be termed the notch strength ratio (NSR). If the NSR is less than 0.5 a material is defined to be very notch sensitive. Note in figure 22 that as the fiber content of tungsten/copper increases the NSR increases. Thus, in the case of tungsten/copper, increasing the proportion of the brittle phase actually reduced composite notch sensitivity (in this case, the overall impact strength of the composite was reduced also, but this does not always happen as will be seen later).

The DBTT of the tungsten fibers in tungsten/copper - 10 nickel was higher than it was in tungsten/copper. This is implied by the fact that the impact strength of tungsten/copper increases greatly between 297 and 420 K ($75^{\circ}$ and $300^{\circ}$ F); however, the impact strength of tungsten/copper - 10 nickel remained constant over the 297 to 420 K ($75^{\circ}$ to $300^{\circ}$ F) temperature range and did not show an increase until the 810 K ($1000^{\circ}$ F) tests. There are two probable reasons for the higher DBTT of the fibers in tungsten/copper - 10 nickel - namely, constraint of the fibers by the copper - 10 nickel matrix and recrystallization caused by diffusion of nickel into the tungsten fibers. That fiber constraint,

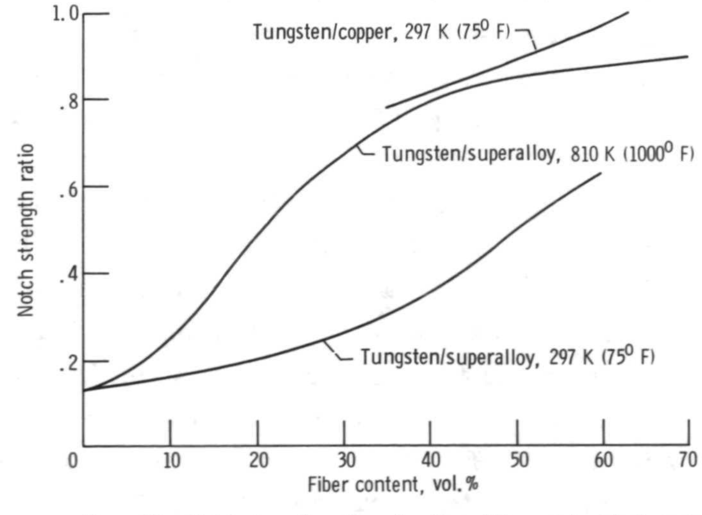



Figure 22. - Notch strength ratio as function of fiber content for tungsten/metal composites tested at 297 and 810 K ($75^{\circ}$ and $1000^{\circ}$ F).

or debonding, could account for the higher DBTT can be reasoned from the behavior of fully recrystallized tungsten fibers in both copper and copper - 10 nickel. The DBTT of the fully recrystallized fibers in copper was less than 810 K ($1000^{\circ}$ F) while the DBTT of the fully recrystallized fibers in copper - 10 nickel was greater than 810 K ($1000^{\circ}$ F) as indicated by abrupt increases in impact strength (tables I and II). Assuming, as before, that the matrices in both composites contributed equally to impact strength, and assuming that the fully recrystallized fibers have the same intrinsic DBTT's outside of a composite, the difference between the DBTT's of the fibers in the two matrices must be a function of debonding. It is possible that the strong bond in tungsten/copper - 10 nickel enables the matrix to constrain the fibers and thereby reduce their effective ductility and, hence, raise their DBTT. That recrystallization raises the DBTT of wrought tungsten has previously been shown (ref. 5). Just how much of the DBTT increase can be attributed to constraint and how much can be attributed to recrystallization cannot be determined from the available data.

## Tungsten/Nickel-Base Superalloy Composite

The fibers in tungsten/superalloy, like those in tungsten/copper and tungsten/copper - 10 nickel, were brittle below their DBTT and ductile above their DBTT. Also, the superalloy reacted with the tungsten fibers to form a recrystallized zone in the perimeter of the fibers similar to that formed in tungsten/copper - 10 nickel. Tungsten/superalloy was studied because it was representative of a class of practical composites having excellent stress-rupture strengths to 1480 K ($2200^{\circ}$ F) (ref. 1).

As with tungsten/copper, the impact strength of tungsten/superalloy was primarily the energy absorbed by elastic-plastic deformation, while debonding indirectly enhanced impact strength at elevated temperatures. The results of impact tests conducted below 530 K ($500^{\circ}$ F) substantiate the first part of the preceding conclusion. There were three possible sources of energy absorbtion in these tests - namely, elastic-plastic deformation, crack propagation, and debonding. But debonding was not a factor because there was no debonding in these tests. Furthermore, the crack propagation energy is seen to be of minor importance by the following reasoning. The impact strength of unnotched specimens was two to ten times that of notched specimens. But, the impact strength of the notched specimens is primarily a measure of the energy required to propagate a crack through the tungsten/superalloy specimen; this implies that crack propagation energy may account for less than one-tenth of the impact strength of unnotched composites. By elimination, it would seem that elastic-plastic deformation is the major factor in energy absorbtion below 530 K ($500^{\circ}$ F). Next, consider the results of impact tests conducted above 530 K ($500^{\circ}$ F). This temperature is the DBTT of the tungsten and is the temperature at which tungsten/superalloy showed an abrupt increase in impact strength (fig. 9). In these tests, unlike those below 530 K (500° F), the tungsten fibers necked in the tension region of the specimen and sheared in the compression region. This improved ductility implied improved toughness which was also noted in tension tests of unreacted tungsten fibers (fig. 23). (In these tests, the toughness was calculated as the area under the stress strain curve.) On the other hand, the impact strength of the unreinforced matrix, and presumably its contribution to composite impact strength, decreased as test temperature increased (fig. 9). Consequently, the abrupt increase in

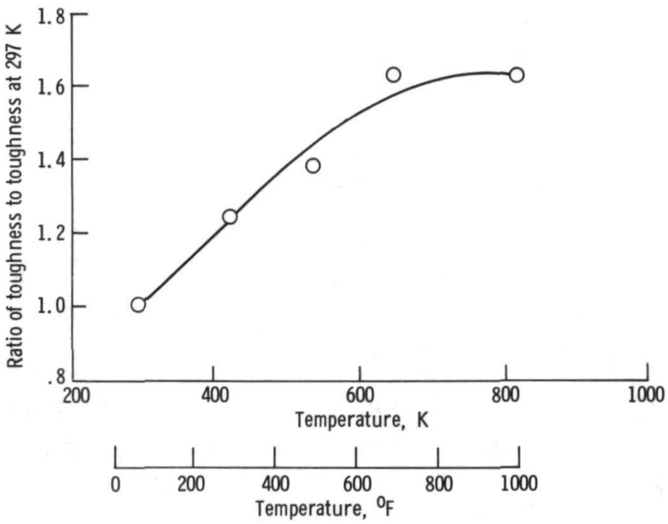



Figure 23. - Ratio of toughness of 0.038-centimeter (0.015-in.) diameter 218CS tungsten fiber at various temperatures to its toughness at 297 K (75° F). Toughness measured as area under tension stress-strain curve.

tungsten/superalloy impact strength at 530 K (500° F) is believed due to increased toughness of the tungsten fibers accompanying their increased ductility. Of course, the effects of debonding must be considered because the fibers debonded from the surrounding matrix. Although the physical separation of fibers and matrix undoubtedly contributed some energy to the impact strength, the authors feel that the primary effect of debonding was to relieve constraints on the fibers. This in turn allowed them to deform plastically to a greater extent than if debonding had not occurred.

The notch sensitivity of tungsten/superalloy decreased with increasing fiber content both above and below the DBTT of the tungsten, much as in tungsten/copper (fig. 22). Note, in particular, that above the fiber DBTT (530 K (500° F)) not only did the NSR increase with increased fiber content but, unlike what happened in tests below the DBTT, impact strength also increased (fig. 9). Therefore, a meaningful way to lower the notch sensitivity of the composite can be to raise fiber content.

Hot working and heat treatment apparently had the effect of toughening the matrix and, thus, improved the 297 K ($75^{\circ}$ F) notched and unnotched impact strength of tungsten/superalloy. Hot working and heat treatment would be expected to improve the impact strength of the matrix by strengthening the bonds among the matrix powder particles, but neither process would be expected to improve the impact strength contribution of the fibers at 297 K ($75^{\circ}$ F) because both processes increase the fiber-matrix reaction (recrystallization) zone depth. The SEM photographs do indicate better bonds among the matrix powder particles in specimens of heat-treated tungsten/superalloy and worked tungsten/superalloy (figs. 20 and 21).

## Variables That Can Affect Composite Impact Strength

The variables considered in this program were fiber toughness, matrix toughness, fiber-matrix reaction, fiber content, notches, test temperature, hot working, and heat treatment. Since elastic-plastic deformation was the principal energy absorbtion mechanism, it was not surprising that varying fiber and matrix toughness or ductility had the greatest effect on composite impact strength. In fact, changing the values of the other variables seemed to affect impact strength indirectly by changing the fiber and/or matrix toughness. In this section the conclusions of the previous sections will be consolidated and expanded to gain an appreciation for the effects and interrelationships of the previously mentioned variables.

As shown in previous sections, impact strength depended on the toughness of the fibers which had a DBTT that depended on the depth of the recrystallized zone in the fibers and the strength of the fiber matrix bond. The greater ductility of the fibers above the DBTT implied greater toughness which was substantiated by tension tests of unreacted tungsten fibers. However, the tension tests indicated a gradual increase in toughness, whereas the impact tests indicated an abrupt increase. Apparently, plastic deformation of the fibers was inhibited below the DBTT by constraints imposed by the matrix. It is not felt that heat treatment or hot working of the composite increased fiber toughness.

In general, the impact strengths of the composites could be a function of matrix toughness or matrix ductility. This conclusion is substantiated by noting that at 297 K ($75^{\circ}$ F) tungsten/copper - 10 nickel had greater impact strength than as-HIP tungsten/superalloy even when the fiber contents and recrystallized zone depths were similar (fig. 24). The fibers in both types of composite should have similar intrinsic properties, and, since no debonding was observed in either composite at 297 K ($75^{\circ}$ F), the difference in impact strength can be ascribed to the fact that copper - 10 nickel was more ductile, and presumably tougher, than the brittle superalloy. As mentioned previously, heat treatment and hot work both seemed to increase the toughness of the as-HIP matrix. A further possible effect of matrix ductility could be to lower the DBTT of the fiber in the composite (ref. 6).

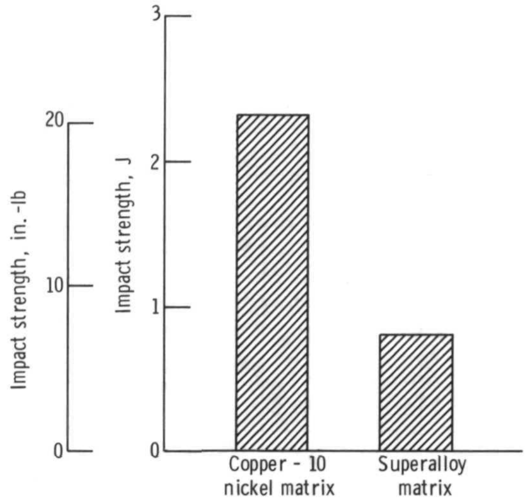



Figure 24. - Impact strength of tungsten/copper - 10 nickel (reaction zone depth, 0.0028 cm) compared to that of tungsten/nickel-base superalloy at 297 K ($75^0$ F), both at 53.5 volume percent.

The authors have developed an empirical equation relating the impact strength of the composite to properties of the fibers and matrix and to fiber content. The equation seems to be valid for both notched and unnotched specimens and is

$$W_c = W_f V_f^2 + W_m \left(1 - V_f\right)^2 \tag{1}$$

where

$W_c$ composite impact strength

$W_f$ impact strength contribution of fibers and bonds in a hypothetical 100 volume percent composite

$W_m$ impact strength of unreinforced matrix

$V_f$ volume fraction of fibers

Both $W_f$ and $W_m$ can be calculated using two or more $W_c$ values with equation (1). Alternatively, $W_m$ can be found directly by impact testing the unreinforced matrix. However, $W_f$ is a curve fitting parameter which may include a debonding component and cannot readily be determined by tests external to the composite. The impact strength $W_f$ must be calculated using values of $W_c$ and $W_m$ with equation (1). For all the plots in this report giving impact strength as a function of fiber content, the curve drawn through the data was least squares calculated using equation (1). The correlation coefficients for these curves were all greater than 0.75 (table VI).

Although equation (1) is empirical, it may be that $W_f$ and $W_m$ have physical sig-

TABLE VI. - CALCULATED $W_m$ (IMPACT STRENGTH OF UNREINFORCED MATRIX) AND $W_f$ (IMPACT STRENGTH CONTRIBUTION OF FIBERS AND BONDS IN HYPOTHETICAL 100 VOL. % COMPOSITE) VALUES FOR VARIOUS 218CS-TUNGSTEN/METAL-MATRIX COMPOSITES

[Notched values multiplied by 1.25 to correct for difference in area between notched and unnotched specimens.]

| Matrix | Temperature, K (°F) | Unnotched | | | | Notched | | | | Correlation coefficient | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | J | | in.-lb | | J | | in.-lb | | | |
| | | $W_m$ | $W_f$ | $W_m$ | $W_f$ | $W_m$ | $W_f$ | $W_m$ | $W_f$ | Unnotched | Notched |
| Copper | 297 (75) | 11.0 | 3.2 | 97.4 | 28.3 | 8.5 | 4.1 | 75.3 | 36.5 | 0.88 | 1.02 |
| Nickel superalloy: as-HIP | 297 (75) | 3.6 | 0.2 | 31.9 | 1.4 | 0.4 | 1.0 | 4.0 | 8.5 | 1.05 | 0.76 |
| | 365 (200) | 3.3 | 0.1 | 29.2 | 0.9 | --- | ----- | ---- | ----- | 0.84 | ---- |
| | 420 (300) | 3.2 | 1.0 | 28.3 | 8.9 | 0.5 | 2.8 | 4.1 | 24.4 | 0.94 | 0.82 |
| | 810 (1000) | 1.5 | 18.3 | 13.3 | 162.0 | 0.2 | 16.6 | 1.9 | 147.0 | 0.78 | 1.08 |
| Heat treated at 1365 K (2000° F) for 100 hr | 297 (75) | 7.2 | 0.7 | 63.7 | 6.5 | --- | ----- | ---- | ----- | 1.00 | ---- |
| Heat treated at 1365 K (2000° F) for 250 hr | 297 (75) | 8.2 | -0.1 | 72.6 | -0.7 | 1.6 | [a]<0.1 | 14.6 | [a]<1.0 | 0.98 | ---- |
| Round rolled at 1365 K (2000° F) to 78 percent area reduction | 297 (75) | [a]17.4 | [a]<0.1 | [a]154.0 | [a]<1.0 | [a]24.6 | [a]<0.1 | 218.0 | [a]<1.0 | ---- | ---- |

[a]Estimated value.

nificance (in fact, $W_m$ obviously does because it is the impact strength of the unreinforced matrix). If it is assumed that they do, the following conclusions, noted earlier, are implied by the $W_f$ and $W_m$ values listed in table VI: The impact strength contribution of the fibers and bonds $W_f$ was not reduced by notching the composite impact specimens, but the impact strength contribution of the matrix $W_m$ could be greatly reduced by notching. These observations can be interpreted to mean that high fiber content specimens, whose impact strengths are controlled predominantly by the $W_f$ term, would be less notch sensitive than low fiber content specimens, whose impact strengths are controlled by the $W_m$ term. Another implication is that the major effect of heat treatment on the as-HIP tungsten/superalloy was to increase the impact strength contribution of the matrix (inferred by comparing $W_m$ values).

Another possibility, assuming equation (1) represents reality, would be to predict the miniature Izod (or perhaps other) impact strength of proposed composite systems. How this could be done is best explained by an example. Suppose that impact strength data were not available for tungsten/copper - 10 nickel, but it was desired to estimate what its impact strength might be. One could assume that the $W_m$ for copper - 10 nickel would be the same as that of copper (a value which you already have). Furthermore, it could be assumed that the $W_f$ of tungsten/copper - 10 nickel would be the same as that of tungsten/superalloy (a value which you already have). When using the assumed values of $W_f$ and $W_m$ with equation (1), a plot of estimated composite impact strength as a function of fiber content can be made for tungsten/copper - 10 nickel. Such a calculated curve is plotted in figure 25. The single applicable data point from table II falls on the calculated curve.

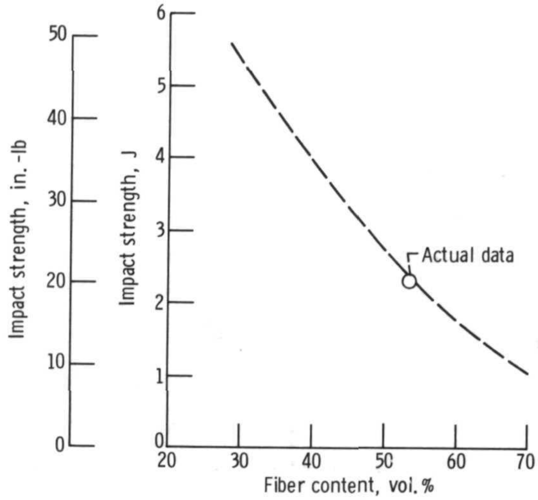



Figure 25. - Impact strength as function of fiber content for tungsten/copper - 10 nickel calculated using equation (1) at 297 K ($75^\circ$ F). Curve calculated assuming the following: impact strength of unreinforced matrix, $W_m$, 11.0 joules (97 in.-lb); impact strength contribution of fibers and bonds in hypothetical 100 volume percent composite, $W_f$, 0.15 joule (1.3 in.-lb).

A further implication of equation (1) is that the impact strength of the composite passes through a minimum as a function of fiber content. The fiber content at minimum impact strength is given by

$$V_f = \frac{W_m}{(W_f + W_m)} \tag{2}$$

And, the minimum impact strength is given by

$$W_c = \frac{W_f W_m}{(W_f + W_m)} \tag{3}$$

Note that the minimum would always be less than half of $W_f$ or $W_m$, whichever is less.

It should be remembered, however, that equation (1) is empirical and relates, at best, only to composites whose chief energy absorbtion is derived from elastic-plastic deformation (minimal debonding contribution). The data of this program were not sufficiently precise to determine if the previous minimum actually exists. Consequently, equations (1) to (3) should be used with extreme caution.

## Impact Resistance of Tungsten/Superalloy Turbine Blades

An objective of this program was to determine if the potential impact resistance of tungsten/superalloy composites was sufficient to warrant their consideration as turbine blade or vane materials. In making this determination based on miniature Izod impact strength, the question arose as to what miniature Izod impact strength corresponded to adequate impact resistance in a turbine blade material. Although attempts have been made by others to define such a standard, the net result is that no agreement has been reached. Standards have been proposed that range from 2.7 to 14.1 joules (24 to 125 in.-lb) and are based, in part, on the superalloy data listed in table VII. The authors feel that these standards are too high for screening values, and their use may result in the rejection of potentially useful materials. To screen the composites tested in this program, a miniature Izod impact strength value of 1.7 joules (15 in.-lb) for an unnotched specimen was selected as the minimum standard. This standard is based on the engine operating experience related by Signorelli et al. in reference 7. It represents the impact strength of a superalloy (Guy alloy) that was run in an engine test as a turbine blade and found to have adequate impact damage resistance (table VII). The authors feel that a composite meeting this minimum standard would have adequate impact strength for at least some turbine blade or vane applications; thus, the material would be worthy of further investigation.

TABLE VII. - UNNOTCHED MINIATURE IZOD IMPACT STRENGTHS USED TO DEFINE SOME MINIMUM IMPACT STRENGTH STANDARDS FOR TURBINE BLADES AND VANES

| Superalloy | Temperature, K ($^{o}$F) | | | |
|---|---|---|---|---|
| | 297 (75) | 1035 (1400) | 1170 (1650) | 1255 (1800) |
| | Impact strength, J (in.-lb) | | | |
| Guy alloy (blades) | 1.31 (11.6) | ------------ | 1.72 (15.2) | ---------- |
| Inconel 713 C (blades) | 14.10 (124.8) | 13.95 (123.5) | ---------- | 4.52 (40.0) |
| WI-52 (vanes) | 3.64 (32.2) | 9.22 (81.6) | ---------- | ---------- |

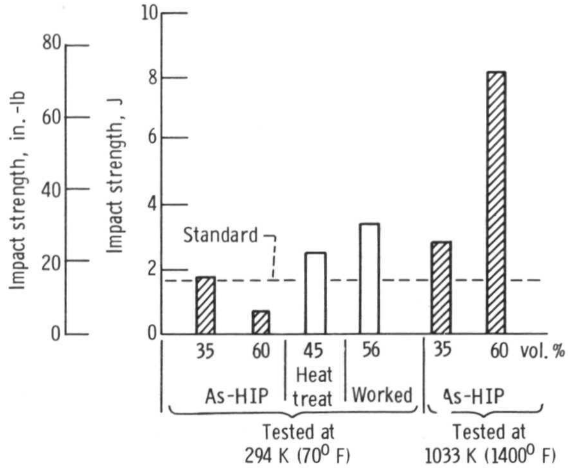



Figure 26. - Miniature Izod impact strengths of unnotched tungsten/nickel-base superalloys compared to minimum impact strength standard used to screen potential turbine blade and vane materials.

Figure 26 depicts a comparison of tungsten/superalloy impact strengths with the minimum standard. The as-HIP composite at 297 K ($75^{\circ}$ F) is considered first. Only those specimens containing less than 35 volume percent fibers exceeded the standard. Thus, in general, tungsten/superalloy composites made using the superalloy matrix and HIP techniques of this program must contain less than 35 volume percent fibers to be acceptable for turbine blades. Newly developed tungsten fibers (W-Hf-C or W-Re-Hf-C) would provide needed blade stress-rupture strengths at fiber contents well under 35 volume percent (ref. 8). However, heat treatment and mechanical working could be used to improve the impact strength of composites fabricated as in this program without sacrificing fiber content (fig. 26). Moreover, the nickel-base superalloy used in this program was originally designed for compatability. No attempt was made to optimize it for toughness, nor was the fabrication procedure optimized to produce an impact resistant composite. The authors are confident that matrix alloys with greater toughness, as well as compatability, can be designed. The use of these matrices combined with improved fabrication procedures would preclude the need for post-fabrication treatments or lower fiber content. For instance, equation (1) suggests that a matrix with an impact strength of only 10 joules (89 in. -lb) would give a 60 volume percent composite adequate impact strength even if the fibers contributed nothing.

At 1035 K ($1400^{\circ}$ F), the higher fiber content as-HIP tungsten/superalloy composites have impact strengths distinctly above the standard (fig. 26). High Charpy values, when area corrected, imply that most of this strength is maintained to at least 1365 K($2000^{\circ}$ F) (table III). The authors feel that these high-temperature impact strengths could be increased by using a tougher matrix as already described. But such improvement may not be required, since the current high-temperature impact strengths of tungsten/superalloy may well be more than adequate for turbine blade and vane applications.

## CONCLUSIONS

The conclusions presented here apply to the studied tungsten/metal matrix composites. However, it is hoped that they will also apply to other fiber/metal matrix composites in which debonding and delamination mechanisms are secondary sources of impact strength.

1. Composite impact strength is strongly dependent on the toughness of the fibers and matrix. Increasing the toughness of either component increases the impact strength of the composite.

2. Increasing the fiber-matrix reaction zone depth lowers composite impact strength (presumably by lowering fiber toughness) and can raise the DBTT of the fiber.

3. The effect of fiber content on composite impact strength depends on the relative impact strength contributions of the fibers and matrix. For instance, if the fibers are brittle relative to the matrix, increasing the fiber content lowers impact strength. An empirical equation that gives the impact strength of the composite ($W_c$) as a function of fiber volume fraction ($V_f$), unreinforced matrix impact strength ($W_m$), and a curve fitting parameter ($W_f$) is

$$W_c = W_f V_f^2 + W_m \left(1 - V_f\right)^2$$

4. Notches affect composite impact strength most when the matrix is notch sensitive and the fiber content is low. The impact strength contribution of the fibers does not seem to be greatly affected by notching.

5. Changing the test temperature changes the toughness of the fibers or matrix. The fibers have a DBTT in the composite which seems to depend on the matrix used and fiber-matrix reaction.

6. Mechanical working or heat treatment can improve the impact strength of some composites.

7. A tungsten/nickel-base superalloy composite can be made with an impact strength adequate for at least some turbine blade and vane applications.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 5, 1973,
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