# NASA TECHNICAL MEMORANDUM

NASA TM X-67810

NASA TM X-67810



# PENDULUM IMPACT RESISTANCE OF TUNGSTEN-FIBER METAL-MATRIX COMPOSITES

by Edward A. Winsa and Donald W. Petrasek
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Second Conference on Composite Materials: Testing and Design
sponsored by the American Society for Testing and Materials
Aneheim, California, April 20-22, 1971

E-6272

# PENDULUM IMPACT RESISTANCE OF TUNGSTEN-FIBER METAL-MATRIX COMPOSITES

by Edward A. Winsa and Donald W. Petrasek

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

## ABSTRACT

The impact properties of pure copper, copper-nickel alloy, and superalloy matricies reinforced with tungsten fibers were studied. The following increased composite impact strength: increased fiber or matrix toughness; increased test temperature; hot working and heat treatment; decreased fiber-matrix reaction. Increasing fiber content increased impact strength above fiber ductile - brittle transition-temperature (DBTT), but lowered it below fiber DBTT. Notch sensitivity was reduced by increasing fiber and/or matrix toughness. Above 533 K (500 F) (fiber DBTT), the superalloy matrix composite had better impact strength than a turbine blade superalloy. Below 533 K (500 F), the composite and superalloy were equivalent.

## INTRODUCTION

Refractory-alloy fiber metal-matrix composites having potential for advanced gas turbine blade and vane application were developed at NASA Lewis Research Center. At high temperatures some of these materials exhibited excellent strength and good corrosion resistance. For instance, a tungsten-alloy-fiber nickel-base-superalloy composite had four times the 1366 K (2000 F) 100 hr rupture strength of a convential high strength superalloy (338 $MN/m^2$ (49,000 psi) vs. 51 $MN/m^2$ (12,000 psi)) ref. (1). A few thousandths of an inch of matrix or cladding protected the tungsten fibers from oxidation at 1366 K (2000 F). Impact resistance is also required for turbine blade applications. A cursory impact study indicated that the above composites had very good high temperature impact strength, but relatively poor room temperature impact strength, ref. (1). Since impact damage may be a problem in turbine blade applications, it was felt that a more detailed study of metal-fiber metal-matrix composite impact behavior was warranted.

The present program had two primary objectives. The first was to determine which of several material parameters could be related to impact strength of tungsten-fiber metal-matrix composites of different types; and, subsequently to reason how such relationships could apply generally to composite resistance to impact. The second objective was to determine whether tungsten-fiber nickel-base superalloy composites previously developed as part of an NASA research effort have adequate impact strength for gas turbine blade and vane applications. The first objective was accomplished by obtaining impact properties for three tungsten-fiber metal-matrix composites. The matrix alloys were copper, copper-nickel, and a nickel-base superalloy. The use of these three composites permitted the variation of the following parameters: fiber toughness, matrix toughness, fiber-matrix reaction, fiber content, notches, test temperature, and post fabrication treatments. Cross comparison of the data was used to relate the impact data for the three systems to the general case. The second objective was accomplished by comparing the impact properties of a tungsten-fiber nickel-base superalloy composite to those of a superalloy. The impact strength of the superalloy represented a minimum impact strength requirement for a turbine blade material.

## MATERIALS, APPARATUS, AND PROCEDURE

### Wire Material

The wire material used for all of the composites of this investigation was commercial, lamp filament, 218 CS tungsten having a diameter of 0.038 cm (0.015 in.). It was received in the as drawn, cleaned and straightened condition. This wire was selected because it had been used in previous programs; and, it is felt that the properties of this wire are representative of tungsten-alloy wire in general.

### Matrix Material

Three different matricies were studied, namely OFHC (oxygen-free, high-conductivity) copper, copper-10 wt. percent nickel, and a nickel-base superalloy. The copper was a nonreactive, ductile matrix; the copper-10 nickel was a ductile but reactive matrix; and the nickel-base superalloy was a brittle and reactive matrix; the nickel superalloy nominal composition was 56 percent nickel, 25 percent tungsten, 15 percent chromium, 2 percent aluminum, and 2 percent titanium. The nickel alloy was vacuum cast and atomized into fine powder with a particle range of -325 to 500 mesh. The composition of the nickel-base material was selected on the basis of its compatibility with tungsten fibers and was taken from the same lot of material used in ref. (1).

## Composite Specimen Fabrication

Composite specimens were fabricated by two methods. The copper and copper-10 percent nickel composite specimens were liquid phase infiltrated at 1478 K (2200 F), 1589 K (2400 F), and 1700 K (2600 F), as decribed in ref. (2); while, the nickel-base superalloy composite specimens were slip cast and isostatically hot pressed at 1089 K (1500 F) and 1366 K (2000 F) as described in ref. (1).

## Rolling and Thermal Treatments

In an earlier study, ref. (1), the room temperature impact strength of tungsten-fiber nickel-base superalloy was found to be relatively poor. This was partially attributed to low matrix toughness caused by poor bonding between the matrix powder particles. Two approaches to strengthening the interparticle bond of the as-fabricated matrix were tried. Some bars of the composite were round rolled to 75 percent reduction in area at 1366 K (2000 F), prior to Izod specimen machining; also, some machined impact specimens were inert atmosphere heat treated at 1366 K (2000 F) for 250 hr, prior to testing.

## Impact Specimen Configuration

All but two of the impact specimens tested for this program were of the miniature Izod configuration. Stetson, et al ref. (3) found that the miniature Izod pendulum impact properties of composite materials correlated very well with their properties measured by various ballistic impact tests. They also indicated that the miniature Izod test should be a reasonable test for screening the impact properties of potential turbine blade and vane materials. The test has the additional advantages of being easy to run and requiring very little material per specimen.

The impact specimens were machined to the following specifications. Two Charpy specimens were machined from composites to ASTM specification "Notched Bar Impact Testing of Metallic Materials" (E 23-66); while the miniature Izod specimens were machined to one-half size of ASTM specification E 23-66. All miniature Izod specimens had a surface finish of 125 microinches or better. The Izod specimens were 0.5 cm by 0.5 cm by 3.8 cm (0.197 in. by 0.197 in. by 1.48 in.). Unnotched and v-notched specimens were machined to both Izod and Charpy configurations.

## Impact Testing Machines

A modified, Bell Telephone Laboratory type, miniature Izod, impact machine was used for most of the impact testing. It was calibrated in accordance with ASTM specification E 23-66 for three energy ranges; these were 0 to 3.05 J (27 in.-lb), 0 to 7.80 J (69 in.-lb), and 0 to 12.9 J (114 in.-lb). The pendulum was set to strike the miniature Izod specimens 22 mm from the grip. The pendulum speed at impact was 348 cm per second (135.8 in. per second).

A standard Charpy impact machine calibrated for 0 to 298 J (220 ft-lb) was used for the two Charpy tests.

## Impact Testing Procedure

Miniature Izod specimens were tested at 297 K (70 F) to 1033 K (1400 F); however, Charpy tests were conducted at 1366 K (2000 F) only.

The miniature Izod specimens were heated with a hot air blower or propane torch while clamped in the impact machine. A thermocouple was used to monitor temperature continuously. After soaking at temperature for 3 to 5 min the specimens were tested. The Charpy specimens were held at 1366 K (2000 F) for 10 min in a resistance wound furnace; then they were transferred to the Charpy machine (with heated tongs) and tested within 5 sec.

## Metallography

The fracture surfaces of tested impact specimens were examined with a scanning electron microscope or binocular microscope to determine the failure characteristics of the matrix and fibers. In addition, longitudinal photomicrographs were taken for some specimens. The fiber content of tested specimens was determined by counting the number of fibers in the transverse section, and multiplying that number by the area of each fiber. The extent of fiber-matrix reaction was determined by measuring the depth of the reaction zone of representative specimens.

## Determination of a Mimimum Impact Criterion

An attempt was made to define a reasonable minimum impact value requirement for turbine blades and vanes. This was necessary to permit evaluation of the potential of a tungsten-fiber nickel-base superalloy to meet turbine blade and vane impact requirements. Since there are no generally accepted minimum impact value standards, the approach was to select a turbine blade superalloy with relatively low miniature Izod impact values at room and elevated temperature, and use these values to define a minimum acceptable standard. The impact values of Guy alloy at 297 K (75 F) and at 1172 K (1650 F) were selected and used to define a minimum acceptable impact value. This value (1.7 J (15 in.-lb) for an unnotched miniature Izod specimen) was selected based on the engine operating experience related in ref. (6). Other investigators have proposed different acceptable values. For instance, Stetson et al ref. (3) felt that the impact values of Inconel 713 C (an established blade material) and WI-52 (an established vane material) were desirable standards. These values are 4.5 J to 14.1 J (40 to 125 in.-lb) and 3.6 J to 9.3 J (32 to 82 in.-lb), respectively.

## RESULTS AND DISCUSSION

### Copper Matrix Composites

Figure 1 is a plot of impact strength as a function of fiber content for tungsten-fiber copper composites tested at 297 K (75 F). Note that the additions of over 20 v/o tungsten fibers, which are brittle at 297 K (75 F), lowered the impact strength of the composites. In contrast, specimens tested at 422 K (300 F) and 811 K (1000 F) showed an increase in impact strength with increasing fiber content (table I). At these temperatures, the impact strength of specimens containing over 20 v/o fibers exceeded the capacity of the impact testing machine which was 12.9 J (114 in.-lb). At these temperatures the tungsten fibers are above their DBTT (ductile brittle transition temperature) and may be considered very tough. The notch impact results shown in Figure 1 are lower than those of the unnotched specimens. However, the notches reduce the cross sectional areas of the specimens by 20 percent. The small difference between the unnotched and notched impact values suggest that the material is not notch sensitive.

## Copper-10 Nickel Matrix Composites

The impact strength of the copper-10 nickel matrix is approximately the same as that of the pure copper matrix. Figure 2 shows impact strength as a function of fiber matrix reaction depth for 60 v/o fiber content composites tested at three different temperatures. In all cases, impact strength decreased with increasing reaction depth and did not increase with test temperature for the composites with very highly reacted fibers.

## Nickel-Base Superalloy Matrix Composites

Figure 3a is a plot of impact strength as a function of fiber content for unnotched tungsten-fiber nickel-base superalloy composites tested at 297 K (75 F) and 811 K (1000 F). Note that impact strength decreases with fiber content at 297 K, but increases with fiber content at 811 K. Figure 3b is a plot of impact strength as a function of fiber content for notched tungsten-fiber nickel-base superalloy composites. Comparison of figures 3a and 3b shows that the notched composites had substantially lower impact values than the unnotched specimens; this indicated that these composites are notch sensitive, especially at low fiber contents and low temperatures. Figure 4 is a plot of impact strength as a function of temperature for unnotched tungsten-fiber nickel-base superalloy composites having 40 v/o and

60 v/o fibers and for the matrix material. The curve for the 60 volume percent composite reveals a DBTT of about 533 K (500 F). The impact strength of the unreinforced matrix decreases with temperature. Figure 5 indicates that the tungsten fibers in the nickel-base superalloy matrix show a transition from brittle fracture to ductile necking when impact tested at 644 K (700 F) and 811 K (1000 F). Necking implies greater fiber toughness. Visual observation of stress strain curves (not shown herein) of tungsten fibers tested in tension at this laboratory, qualitatively indicate a similar increase in toughness with increasing temperature. The increased toughness was indicated by increased areas under the stress strain curves.

Heat treatment at 1366 K (2000 F) nearly doubled the 297 K (75 F) impact strength of a 45 v/o as-fabricated tungsten-fiber nickel-base superalloy composite (2.5 J (22 in.-lb) compared to 1.4 J (12 in.-lb)); and increased the impact strength of the notched unreinforced matrix from 0.34 J (3 in.-lb) to nearly 1.4 J (12 in.-lb). Mechanical working by round rolling to 75 percent reduction in area increased the 297 K (75 F) impact strength of a 54 v/o composite from 0.90 J (8 in.-lb) to over 3.4 J (30 in.-lb), and eliminated notch sensitivity.

The two Charpy specimens tested at 1366 K (2000 F) had the following impact strengths: unnotched - 39.3 J (29 ft-lb), notched - 37.3 J (27.5 ft-lb).

## Fiber Toughness and Its Relationship to Composite Impact Strength

The impact strength of the composites studied seemed to be largely dependent on the fiber's toughness (ability to absorb energy by elastic or plastic deformation). This conclusion is deduced from the fact that the large increases in composite impact strength with increasing temperature corresponded to toughness increases of the fiber, (the toughness increases in the fiber were indicated by the previously mentioned tension tests and by increased ductility observed in scanning electron microscope photos). Similarly, decreasing composite impact strength is attributed to decreasing fiber toughness. The impact strength of the copper-10 nickel composite decreased with increasing fiber-matrix reaction depth (Fig. 2). The reaction zone is brittle and lowered the overall toughness of the tungsten fibers. Ref. (2) described a similar embrittling effect. Thus, when the tungsten fibers were relatively tough (above DBTT), composite impact strength increased with increasing fiber content. But, when the fiber were relatively brittle (below DBTT), composite impact strength decreased with increasing fiber content.

Notches seem to be deleterious to composite impact strength when both fibers and the matrix lack toughness. In this study, when the fibers were tough (above DBTT) at 811 K (1000 F) (Fig. 3b) or the matrix ductile (Fig. 1), notch sensitivity was reduced.

Matrix Toughness and Its Relationship to Composite Impact Strength

The influence of the matrix on composite impact strength may be deduced from comparisons of superalloy-matrix composite and copper-nickel matrix composite data. The copper-10 nickel composite exhibits greater toughness than the superalloy composite, Fig. 2 and 3a. Since it is felt that the tungsten fibers and fiber-matrix reactions are similar in both of these composites, differences in the impact properties can be attributed to matrix differences. The nickel-superalloy matrix is brittle and notch sensitive; whereas, the copper-10 nickel matrix is ductile and notch insensitive i.e., the copper-10 nickel matrix has higher impact strength than the nickel-superalloy matrix, 6.8 J (60 in.-lb) vs 3.4 J (30 in.-lb). Apparently, the role of the matrix relative to composite impact strength parallels that of the fiber, in that, increasing matrix toughness increased the composite's impact strength, while decreasing matrix notch sensitivity decreased composite notch sensitivity.

## Empirical Expression for Composite Impact Strength

The authors have derived an empirical relationship which characterises the impact strength of the five composite systems reported in this study (tungsten, copper - notched and unnotched; tungsten, copper-10 nickel; tungsten, nickel superalloy - notched and unnotched). The expression relates the composite impact strength to that of each component. The equation shown below was derived by visually evaluating the degree of fit of several different equations, and selecting the one with the best fit.

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

where:

$W_c$ the impact strength of the composite

$W_f$ the apparent impact strength of a hypothetical composite containing 100 percent fibers

$W_m$ the impact strength of a specimen of unreinforced matrix

$V_f$ the volume fraction fiber content

Figure 6 shows two impact vs fiber content curves for nickel-base superalloy matrix composites calculated using equation (1); the experimental data points are superimposed. The calculated curves fit the data quite well, within the limits of experimental accuracy. The calculation of the curves shown in figure 6 requires determination of $W_m$ and $W_f$ values. $W_m$ can be obtained directly by impact testing one or more unreinforced matrix specimens. $W_f$ cannot be readily determined by impact tests external to a composite; it must be calculated using one or more values of $W_c$ and solving equation (1) for $W_f$. The accuracy of $W_f$ is dependent on the accuracy of $W_c$.

## Superalloy Composite Turbine Blade Impact Potential

The ability of the tungsten-fiber nickel-base superalloy composite to meet turbine blade and vane impact criteria was evaluated by comparing its impact strength to a minimum criterion of 1.7 J (15 in.-lb). As shown in Fig. 7, at 297 K (75 F), the impact strength of an as-fabricated 35 v/o composite was slightly greater than 1.7 J (15 in.-lb); but, the impact strength of a 60 v/o as fabricated composite was only 0.7 J (6 in.-lb). However, heat treatment and mechanical working could be used to improve the composite's 297 K (75 F) impact strength without sacrificing fiber content, as shown in Fig. 7. Note that the nickel-base superalloy matrix used in this program was originally designed for compatibility; and, no attempt was made to optimise it for toughness. It is conceivable that matrix alloys having greater toughness as well as compatibility can be designed; and, use of these matrices combined with improved fabrication procedures would produce a composite with greater impact strength.

At 1033 K (1400 F), the as-fabricated nickel-base superalloy composites have impact strengths distinctly above the minimum criterion (Fig. 7). The high Charpy values 37.3 J (27.5 ft-lb) and 39.3 J (29 ft-lb) indicate that most of this strength is maintained to 1366 K (2000 F).

From the foregoing it is concluded that: tungsten-fiber nickel-base superalloy composites can be made having impact strength adequate for turbine blade and vane use.

## SUMMARY OF RESULTS

1. At 297 K (75 F), the impact strength of the as-fabricated tungsten-fiber nickel-base superalloy composite decreased with fiber content from 3.4 J (30 in.-lb) at 0 v/o to 0.7 J (6 in.-lb) at 60 v/o. However, at 811 K (1000 F), the impact strength increased with fiber content from 1.4 J (12.5 in.-lb) at 0 v/o to 8.1 J (72 in.-lb) at 60 v/o. The composite had a ductile-brittle transition temperature of 533 K (500 F); however, it was notch sensitive at all test temperatures and fiber contents.

2. Heat treatment nearly doubled the 297 K (75 F) impact strength of a 45 v/o as-fabricated nickel-base superalloy matrix composite (1.4 K (12 in.-lb) to 2.5 J (22 in.-lb)). Hot working quadrupled the impact strength of a 55 v/o as-fabricated nickel-base superalloy matrix composite (0.9 J (8 in.-lb) to 3.5 J (31 in.-lb)), and eliminated notch sensitivity.

3. The 297 K (75 F) impact strengths of the copper matrix composite decreased with increasing fiber contents over 20 v/o. At 422 K (300 F)

and 811 K (1000 F) impact strength increased with fiber content. Also, these composites were not notch sensitive.

4. The impact strength of the copper-10 nickel matrix composite decreased with increased fiber-matrix reaction depth.

5. The impact strength of all the composite systems studied could be characterized by a single empirical equation.

## CONCLUSIONS

1. Increasing fiber or matrix toughness increases the impact strength of the composite. The impact strength of the composite tends to increase with increasing fiber content when the fiber is tough relative to the matrix, and tends to decrease when the fiber is brittle relative to the matrix. However, at some fiber content (other than 0 v/o or 91 v/o) impact strength may be a minimum. The impact strength of tungsten fiber composites decreases as fiber-matrix reaction depth increases.

2. Notches are most deleterious to composite impact strength when both fibers and matrix lack toughness.

3. A tungsten-fiber nickel-base superalloy composite can be made with impact strength adequate for turbine blade and vane use.

## REFERENCES

1. Petrasek, D. W., and Signorelli, R. A., "Preliminary Evaluation of Tungsten Alloy Fiber-Nickel-Base Alloy Composites for Turbojet Engine Applications," NASA TN D-5575, Nat. Aeronautics and Space Administration, 1970.

2. Petrasek, D. W., and Weeton, J. W., "Alloying Effects on Tungsten-Fiber-Reinforced Copper-Alloy or High-Temperature-Alloy Matrix Composites," NASA TN D-1568, Nat. Aeronautics and Space Adminis Administration, 1963.

3. Stetson, A. R., Ohynsty, B., Akins, R. J., and Compton, W. A., "Evaluation of Composite Materials for Gas Turbine Engines," AFML-TR-66-156, pt. 1, AD-487290, Solar, June 1966.

4. Ohnysty, B., and Stetson, A. R., "Evaluation of Composite Materials for Gas Turbine Engines," AFML-TR-66-156, pt. 2, AD-825844, Solar, December 1967.

5. Ohnysty, B., Moore, V. S., Stetson, A. R., and Compton, W. A., "Test Manual - Evaluation of Composite Materials for Gas Turbine Engines, Part 3," RDR-1391-8, AFML-TR-66-156, pt. 3, AD-831243, Solar, March 1968.

6. Signorelli, R. A., Johnston, J. R., and Weeton, J. W., "Preliminary Investigation of Guy Alloy as a Turbojet-Engine Bucket Material for Use at 1650° F," NACA RM E56119, Nat. Aeronautics and Space Administration, 1956.

TABLE I. - IMPACT STRENGTH VALUES OF TUNGSTEN-FIBER COPPER-MATRIX COMPOSITES

Unnotched miniature Izod specimens

| Temperature, K | Temperature, F | Fiber, v/o | Impact strength, joule | Impact strength, in.-lb | Remarks |
|---|---|---|---|---|---|
| 422 | 300 | 0.0 | 5.57 | 49.3 | Specimen bent |
| ↓ | ↓ | 0.0 | 7.26 | 64.3 | ↓ |
| ↓ | ↓ | 1.5 | 7.98 | 70.6 | ↓ |
| ↓ | ↓ | 7.8 | 10.71 | 94.8 | ↓ |
| ↓ | ↓ | 45.0 | >12.88 | >114.0 | ↓ |
| ↓ | ↓ | 56.0 | >12.88 | >114.0 | ↓ |
| ↓ | ↓ | 72.0 | >12.88 | >114.0 | ↓ |
| 811 | 1000 | 54.6 | >12.88 | >114.0 | ↓ |

Room temperature data on figure 1.

E-6272

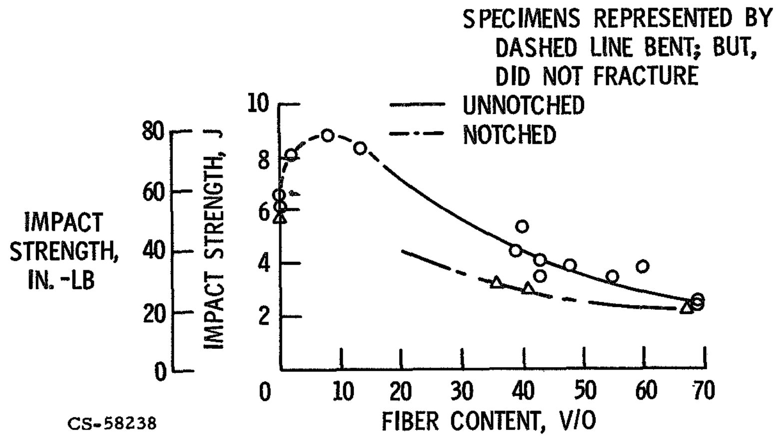



Figure 1. - Room temperature impact strength as a function of fiber content for tungsten-fiber copper-matrix composites.

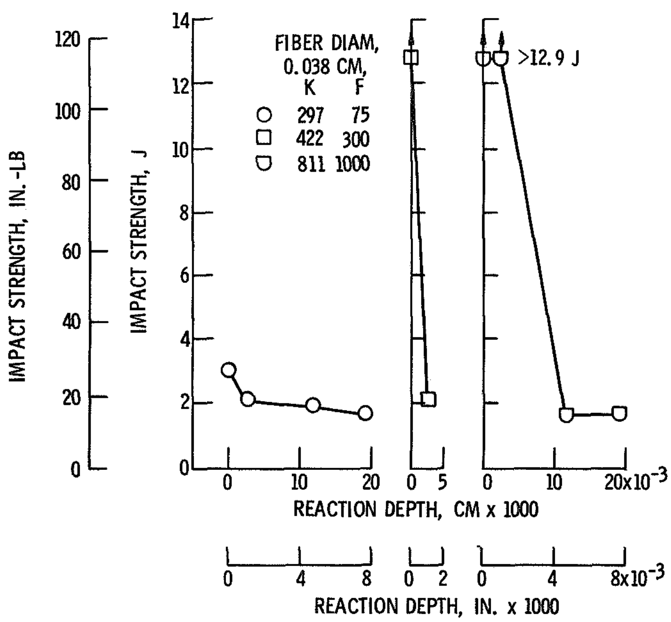
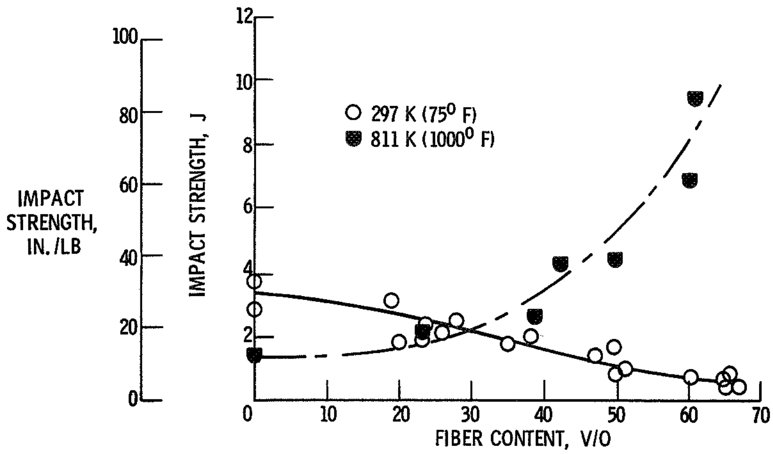


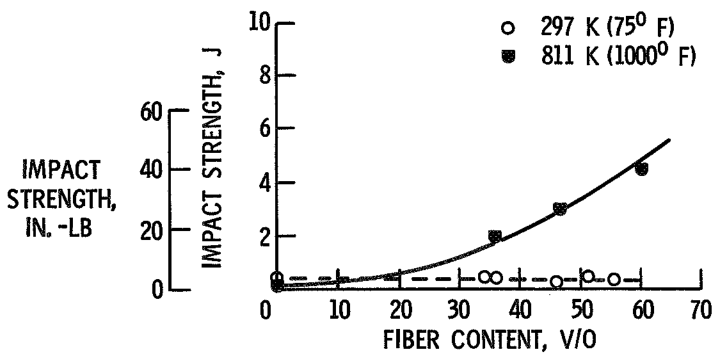

Figure 2. - Impact strength as a function of fiber-matrix reaction depth for unnotched, tungsten-fiber copper-nickel-matrix composites, 60 V/O fibers.

E-6272




(A) UNNOTCHED, AS-FABRICATED TUNGSTEN-FIBER NICKEL-BASE SUPERALLOY COMPOSITES.

Figure 3. - Impact strength as a function of fiber content.




CS-58243

(B) NOTCHED, AS-FABRICATED TUNGSTEN-FIBER NICKEL-BASE SUPERALLOY COMPOSITES.

Figure 3. - Concluded.

E-6272

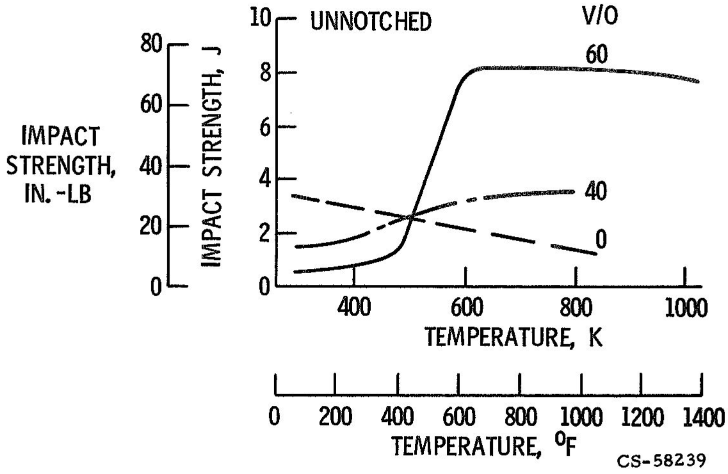
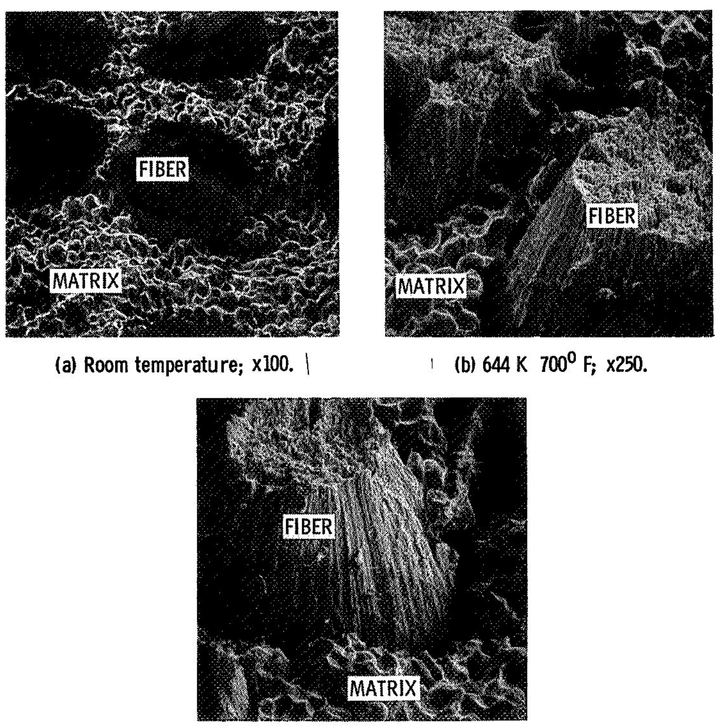



Figure 4. - Impact strength as a function of temperature for unnotched, as-fabricated tungsten-fiber nickel-base superalloy composites having various fiber contents.



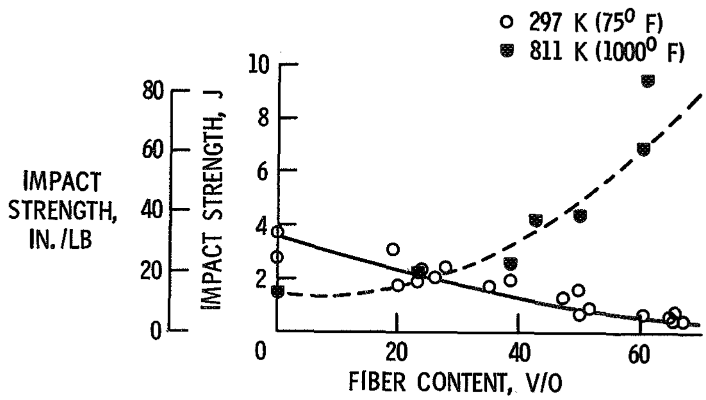

(a) Room temperature; x100.

(b) 644 K 700° F; x250.

(c) 811 K 1000° F; x250.

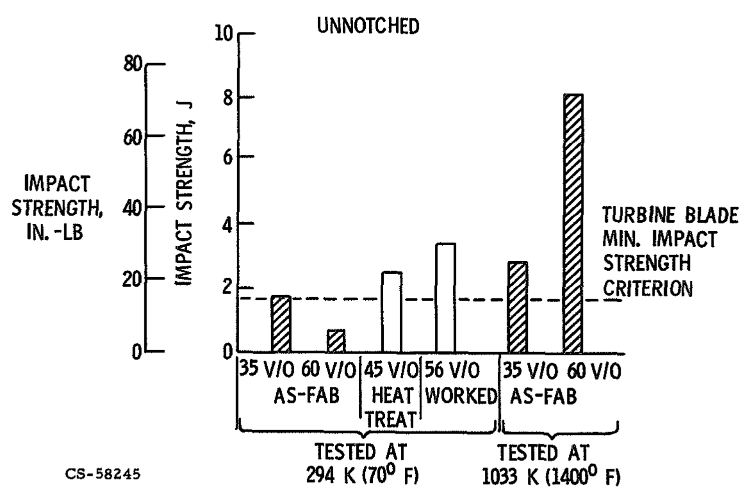
Figure 5. - Scanning Electron Microscope photos of fracture surfaces of as fabricated, unnotched tungsten fiber - nickel-base superalloy composites tested at temperatures indicated.

E-6272




CS-58242

Figure 6. - Impact strength versus fiber content curves generated by empirical equation with superimposed tungsten-fiber nickel-base superalloy composite data.




CS-58245

Figure 7. - Izod impact strengths of unnotched tungsten-fiber nickel-base superalloy composites compared to minimum impact criterion for turbine blades and vanes.