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Progress Toward a Tungsten Alloy Wire/High Temperature Alloy Composite Turbine Blade

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ABSTRACT

A tungsten alloy wire reinforced high temperature alloy composite is being developed for potential application as a hollow turbine blade for the advanced rocket engine turbopumps. The W-24Re-HfC alloy wire used for these composite blades provides an excellent balance of strength and wire ductility. Preliminary fabrication, specimen design, and characterization studies were conducted by using commercially available W218 tungsten wire in place of the W-24Re-HfC wire. Subsequently, two-ply, 50 vol% composite panels using the W-24Re-HfC wire were fabricated. Tensile tests and metallographic studies were performed to determine the material viability. Tensile strengths of a Waspaloy matrix composite at 870 °C were 90% of the value expected from rule-of-mixtures calculations. During processing of this Waspaloy matrix composite, a brittle phase was formed at the wire/matrix interface. Circumferential wire cracks were found in this phase. Wire coating and process evaluation efforts were performed in an attempt to solve the reaction problem. Although problems were encountered in this study, wire reinforced high temperature alloy composites continue to show promise for turbopump turbine blade material improvement.

INTRODUCTION

The Space Shuttle Main Engine (SSME) is the most advanced reusable rocket engine in service. Its high pressure turbopump turbine blades operate in a very challenging environment of high pressure steam and hydrogen. During the development and early operation of the SSME, the durability of these blades was limited to only a few engine firing cycles. Table 1 compares thermal transient data as well as several other characteristics of both rocket and aircraft engines. The high heat transfer coefficient resulting from the high pressure gas causes extremely severe thermal transients in the blade material. In addition, the gas bending loads, as suggested by the high power extraction per blade, causes high steady state loads compared to aircraft engines. While many of the problems which limited the life of the blades have been minimized, their occurrence highlighted the need for improved turbine blade materials for advanced engines. However, the development of advanced superalloys for rocket engine application is believed to offer only about another 80 °C growth to about 950 °C [1].

Studies initiated by the Lewis Research Center about 10 years ago suggested that tungsten wire/superalloy matrix composites offered the potential to improve both performance and durability of SSME type turbine blades. Several matrices (Waspaloy, Incoloy[a] 903, FeCrAlY, and type 316L stainless steel) composited with commercially available W alloy (1.5% ThO_2) wire were investigated [2]. The performance of these composites was evaluated relative to the requirements of SSME blades and compared to MAR-M[b] 246 + Hf, the current blade material. That work showed that the experimental composites performed well. Of the matrices investigated, Waspaloy was selected for further study because of its higher strength at elevated temperatures (Figure 1) [2], therefore lending to better resistance to transverse loads in a unidirectional composite. When properties were projected for composites made with a high strength W alloy (W-4Re-HfC) wire, the composite appeared to be a viable blade material which would be superior to currently available superalloys.

The use of W wire in the composite blade causes an increase in the density of the blade material and some redesign of the SSME high-pressure fuel pump blade was necessary. A two-ply, hollow composite blade was designed that caused no increase in the centrifugal stress imposed on the turbine disk when compared to the current solid MAR-M 246 blades.

This paper discusses progress in the development of a refractory metal wire/high temperature alloy matrix composite for rocket engine turbine blades. This investigation was performed to verify the strength projections made earlier for high strength W-4Re-HfC wire. Because W-4Re-HfC wire is currently not available, another high-strength W alloy, W-24Re-HfC wire, was used in the study.

REFRACTORY METAL WIRE

Refractory metal wires in general have been reported to exhibit a good balance of high strength and ductility, mostly as a result of the drawn grain structure and alloying additions [3]. Initial work at the Lewis Research Center was directed to develop a tungsten fiber reinforced superalloy (TFRS) composite turbine blade for aircraft engines [4]. However, until better high temperature wire became available, no large benefit appeared to be available for rocket engine use. Recently W-24Re-0.4HfC wire (0.036 mm diameter) has been produced in limited amounts and is being evaluated as high-temperature composite reinforcement.

Rhenium has been shown by Klopp et al. [5] to provide ductility enhancement in W/HfC alloys by decreasing the ductile-to-brittle transition temperature. The HfC addition effectively helps to increase the high temperature tensile strength of the tungsten alloy by impeding material deformation at high temperatures [6,7]. This occurs because high Orowan stresses are generated during plastic flow in the structure by dislocation looping around the homogeneously arranged HfC dispersoids [3]. As the temperature of the wire material increases, subgrain and dislocation mobility increases and the HfC plays an increasing role in strengthening. Yun [3] reports that the addition of Re to the wire alloy makes wire drawing easier by increasing the amount of mobile subgrains in the structure. The W-24Re-HfC wire used in this study was prepared under contract by a vacuum arc-melting technique. Pure W and rhenium metal powders were blended in argon, isostatically pressed, then sintered in a hydrogen furnace to produce 2.5 cm diameter alloy bars. Bundles of six sintered bars were spot welded together to act as electrodes. The Hf and C additions were inserted as foil and graphite yarn respectively to achieve the 0.3% Hf and 250 ppm C in the desired alloy. The electrodes were vacuum arc-melted into a water-cooled 9 cm diameter copper mold. The cast ingots were then machined to 6.7 cm diameter, inserted into Mo extrusion cans, and extruded through 2.9 cm extrusion dies. The Mo can was removed from the extruded bar. Subsequently, the extruded bar was hot swaged and then drawn to the final size of 0.36 mm.

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[a]Incoloy is a registered tradename of Inco Alloys International.

[b]MAR-M is a registered tradename of the Martin Marietta Corporation.

Wire Properties and Discussion

The strengths as a function of temperature for W-24Re-HfC, W218, and MoHfC are shown in Figure 1 [3,8]. The densities of W218 and W-24Re-HfC wires are 19.3 [3], [9] and 19.58 g/cm^3, respectively. MoHfC wire (density 10.2 g/cm^3) also shows good potential for high-temperature composite application, with a specific strength similar to the W-24Re-HfC wire.

The mechanical properties of different W-24Re-HfC wire lots used in this study varied. Yun [3] observed this in evaluations of four different lots of wire. The room temperature strength value of 3250 Mpa for one of the lots is thought to be the highest ever observed for a refractory metal alloy [3]. The average strength of W-24Re-HfC wire is shown in Figure 2. The range of reduction-in-area values for all W-24Re-HfC wires tested by Yun at 870 °C was between 60 and 75%. Yun [3] also reports that recrystallization of the W-24Re-HfC alloy occurs at 1427 °C after a 1 hr exposure. Figure 3 compares the predicted rule-of-mixtures strength at 1093 °C of various 50 vol% refractory metal wire/Waspaloy matrix composites. From this figure it can be seen that the W-24Re-HfC wire composite is superior to MAR-M 246.

The thermal processing involved in the fabrication of the composite was postulated to degrade the wire strength. To validate this assumption, both W-24Re-HfC and W218 wire samples were heat treated in an argon atmosphere at 1150 °C for 30 min to simulate the thermal exposure during the HIP portion of the composite fabrication process. After the above heat treatment, the W-24Re-HfC wire tensile strength at 870 °C was 2095 MPa as compared to 2308 MPa for the as-received wire (Figure 2). Similarly, the W218 wire tensile strength at 870 °C after heat treatment was 710 MPa compared to 930 MPa in the as-received condition. Therefore, as was expected, the wire reinforcement exhibited a degradation in properties from the thermal processing. This result affects the final composite strengths. Figure 4 shows the fracture surfaces of both the W-24Re-HfC and W218 wires tensile tested at 870 °C after heat treating at 1150 °C. In both cases, wire necking occurred after the heat treatment, with the final failure mode being of a ductile nature with some tearing. The reduction in area after thermal processing for the W-24Re-HfC was 74% while that of the W218 was 67%.

MATRIX

Two principal requirements for a matrix in a unidirectional turbine blade composite are that it has good strength and ductility. Higher strength and good ductility provide for resistance to transverse loads and better fatigue resistance during engine operation. Waspaloy was selected as a matrix for TFRS investigation because of its high-temperature strength advantage over other candidate matrices as well as its good balance of other properties (Figure 1) [2]. The ultimate tensile strength of wrought at Waspaloy 870 °C is 524 MPa [10]. However, arc-sprayed Waspaloy could show lower strength than wrought Waspaloy. To determine the strength contribution arc-sprayed Waspaloy makes to the composite, monolithic test specimens were fabricated by arc-spraying and HIPing and tensile tested. The results verified the presumption of lower tensile properties as the arc-sprayed strength of 289 MPa was only about 55% of the published wrought strength.

COMPOSITE DEVELOPMENT

The use of high-strength wire such as W-24Re-HfC for composite reinforcement is required to offer advantages over current materials for potential rocket engine turbine blade application. Initially, however, a commercial lamp filament, 218 CS W wire (W218), was used to develop the fabrication procedures and specimen design in place of the W-24Re-HfC wire.

Single-ply TFRS monotapes were fabricated by the arc-spray process developed by the Lewis Research Center. Detailed explanation of this procedure is given in reference 11. The single-ply monotapes fabricated in this study measured 5X99 cm. They were cut into 5X15 cm pieces for composite panel fabrication. Two-ply panels containing 50 vol%, unidirectional wire reinforcement

(Figure 5) were consolidated for this investigation since a preliminary hollow turbopump turbine blade design uses the same ply configuration. HIPing was chosen as the method of consolidation.

Because of the stronger wire used in the present study, it appeared that the pin shear from pin loading may occur through the matrix in the grip area at elevated temperatures during uniaxial testing. Haynes 230 tabs (0.13 cm thick) were therefore added to the composite test panels to increase the shear area so that the calculated shear stress in all shear areas exceeded the calculated breaking strength of the gage. This was effectively accomplished by adding the tabs before consolidation so that they would become diffusion bonded to the Waspaloy matrix, two-ply composite. Figure 6 shows a schematic of this. Figure 7 shows both the composite panel and test specimen.

Reaction Layer

Hot isostatic pressing (HIP) resulted in full densification of the W/ Waspaloy composites. Figure 8 shows a transverse view of the W218/Waspaloy. An intermetallic phase formed at the W218/Waspaloy interface during processing. The thickness of the layer measured 1.6 μm and no cracking was observed. Because the W218/Waspaloy composite was only used to characterize fabrication and test specimen parameters, no further analysis on this material was conducted.

HIPing of the W-24Re-HfC wire reinforced Waspaloy using similar HIP parameters also resulted in complete densification. Figure 9 shows both high and low magnification micrographs of a transverse section. It is evident from the lower magnification that the wire distribution in the composite was very good. The higher magnification, however, shows evidence of cracks in the reaction zone of 1.62 μm thickness that formed during processing. The cracks are believed to be detrimental to the material for rocket engine operation. Figure 10 shows that during further heat treatment of 1080 °C/1 hr/AC + 843 °C/ 24 hr/AC + 760 °C/16 hr/AC the brittle reaction layer grew to a thickness of 3.34 μm, cracked significantly, and debonded from the wire. This heat treatment is typical of those used to develop optimum strength in Waspaloy. The cracking could decrease load transfer from matrix to wire during operation. The heat treated composite had voids present in the wire near the reaction zone, probably caused by the Kirkendall effect. Transmission electron microscopy and micro diffraction were used to identify the W-24Re-HfC/Waspaloy reaction zone as a μ phase. Scanning electron microscopy and electron dispersive spectroscopy identified Ni, Co, W, and Re as its principal elements.

Several approaches were taken to reduce cracking in the W-24Re-HfC/ Waspaloy composite. One method was sputtering diffusion sinks onto the wire. Nominally 25 μm of W or Ni were deposited onto two separate wire lengths. Tungsten was added to tie up any element diffusing from the wire to the reaction zone while N deposition was to dilute Waspaloy element diffusion. Initial results showed that neither Ni nor W completely eliminated the cracked reaction layer. Figure 11 shows cracking still occurred with a W coating. A second corrective approach was to modify the processing. A composite sample was consolidated at a 70 °C lower temperature while the pressure and time were the same as used previously. Results of this effort are promising. Figure 12 shows that even at the lower HIP temperature full consolidation of the matrix was achieved. Figure 12 also shows that the reaction layer was free of cracking. It is also noted that no Kirkendall voids existed in the wires HIPed at the lower temperature.

Preliminary Mechanical Evaluation

Rule-of-mixtures (ROM) calculations were made using the data obtained on the heat-treated W and W alloy wires and the arc-sprayed Waspaloy matrix. For a nominally 50 vol% composite, ROM tensile strength values at 870 °C are 1192 MPa and 496 MPa for W-24Re-HfC/Waspaloy and W218/Waspaloy respectively. The 1192 MPa strength of the W-24Re-HfC/Waspaloy composite is about twice the strength of the current bill of materials superalloy. Figure 13 compare ROM predictions based on actual fiber and matrix tensile data and the actual composite strengths for both composites. The tensile strength of the W-24Re-HfC/Waspaloy composite from the higher temperature HIP run was 91% of the ROM value. The W218/Waspaloy composite strength was 107% of ROM. These values indicate that composite fabrication does not degrade tensile behavior of the composite beyond that which is attributed to thermal degradation of the tungsten alloy wire. The cracked reaction zone does not appear to degrade the tensile strength of the composite.

CONCLUSION

Incorporating a high-temperature W-24Re-HfC alloy wire into a high-temperature matrix holds promise for eventual turbine blade application. The W-24Re-HfC wire investigated could be an excellent reinforcement candidate because of its excellent strength and ductility. Processing improvements of a Waspaloy matrix composite have reduced the cracking in the wire/matrix reaction zone observed in the composite.

ACKNOWLEDGMENT

The authors acknowledge the assistance of P. Book and S. Farmer in identification of the μ phase in the reaction zone.

REFERENCES

1. D.W. Petrasek and R.A. Signorelli, "Tungsten Fiber Reinforced Superalloys-A Status Review," 1981, NASA TM-82590.

2. J.R. Lewis, "Design Overview of Fiber-Reinforced Superalloy Composites for Space Shuttle Main Engine," Advanced High Pressure O_2/H_2 Technology, edited by C.F. Morea and S.T. Wu, 1985, NASA CP-2372, pp. 93-109.

3. H.M. Yun, "Preliminary Evaluation of Tensile and Stress-Rupture Behavior of W + 24a/oRe + 0.4a/oHfC Wire," 1992, To be published.

4. D.W. Petrasek and R.A. Signorelli, "Stress-Rupture Strength and Microstructural Stability of Tungsten-Hafnium-Carbon-Wire-Reinforced Superalloy Composites," 1974, NASA TN D-7773.

5. W.D. Klopp and W.R. Witzke, "Mechanical Properties of Arc-Melted Tungsten-Rhenium-Hafnium-Carbon Alloys," 1969, NASA TN D-5348.

6. G.W. King, G.W., "An Investigation of the Yield Strength of a Dispersion-Handened W-3.8 VolPCT ThO_2 Alloy, AIME Trans, Vol. 245, No. 1, 1969, pp. 83-89.

7. H.M. Yun, "Tensile Behavior of Tungsten and Tungsten-Alloy Wires from 1300 to 1600K," Refractory Metals - State of the Art, 1988, edited by P. Kumar and R.L. Ammon, The Metall. Soc. of AIME, 1988, pp. 49-64.

8. Yun, H.M., "Tensile Behavior of Tungsten and Tungsten-Alloy Wires from 1300 to 1600K," 1988, NASA TM-101446.

9. Metals Handbook, American Society for Metals, Metals Park, OH, 1948.

10. INCO High Temperature, High Strength Nickel Base Alloys booklet. International Nickel Inc., Saddle Brook, NJ, 1984.

11. L.J. Westfall, "Tungsten Fiber Reinforced Superalloy Composite Monolayer Fabrication by an Arc-Spray Process," 1985, NASA TM-86917.

TABLE 1.—COMPARISON OF REUSABLE ROCKET ENGINE AND AIRCRAFT ENGINE TURBINE OPERATIONS

Item	Rocket engines	Aircraft engines
Fuel	Hydrogen or methane	Petroleum distillate
Oxidizer	Oxygen	Air
Pressure, psi	5500	500
Speed, rpm	36 000 to 110 000	15 000
Tip speed, ft/sec	1850	1850
Horsepower/blade	630	200 to 500
Inlet temperature, °F	1600 to 2200	2800
Heat transfer coefficient, Btu/ft^2-hr-°F	54 000	700
Thermal transients, F/sec	32 000	100
Starts		
Life, hr	55 to 700	2000 to 8000
	7.5 to 100	15 000

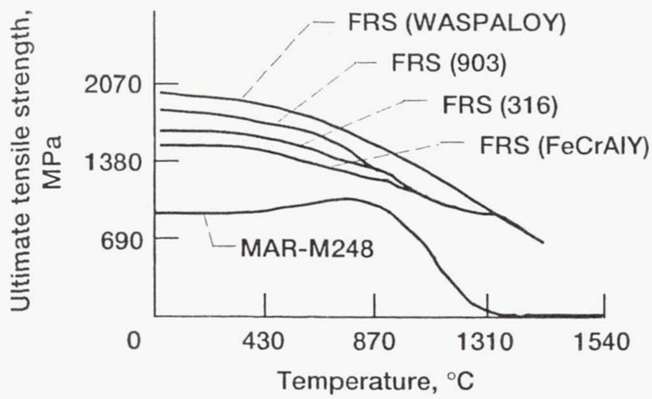


Figure 1.—Projected tensile strengths of candidate TFRS composites. Lewis, 1983

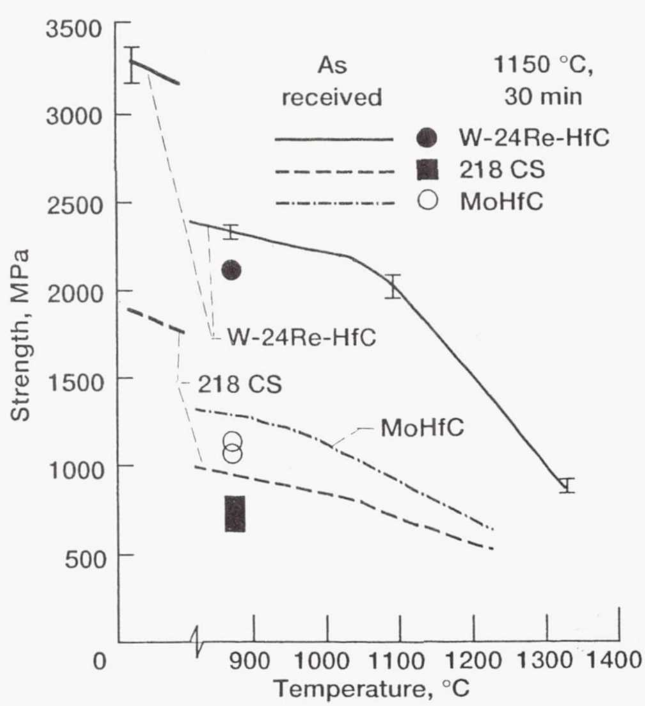


Figure 2.—The effect of temperature on the strength of reinforcement wires.

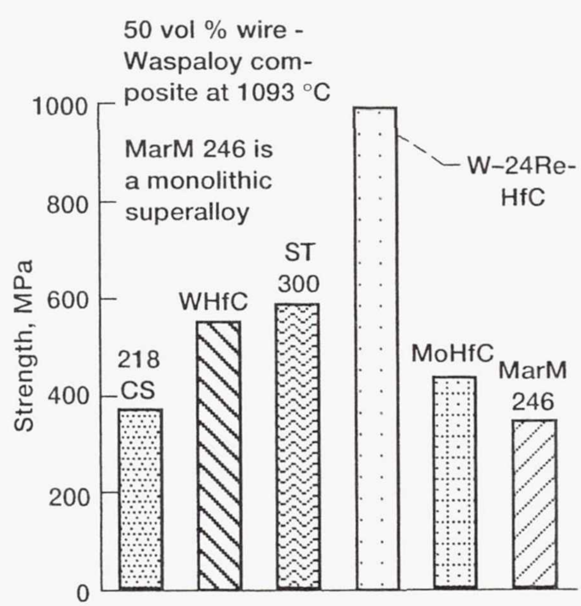
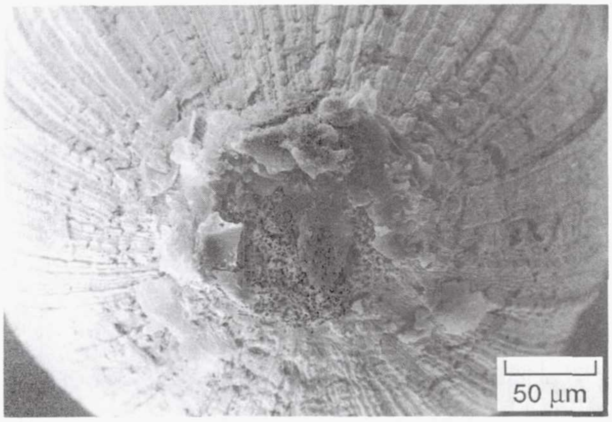


Figure 3.—Composite strength is strongly influenced by wire strength. Only W-24Re-HfC has a large strength advantage over single crystal superalloys.



(a) W-24Re-HfC.

(b) W218.

Figure 4.—Scanning electron micrograph show that both W-24Re-HfC and W218 have ductile fractures at 870 °C after prior heating to 1150 °C.

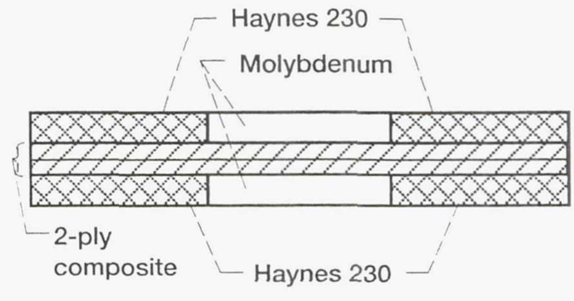
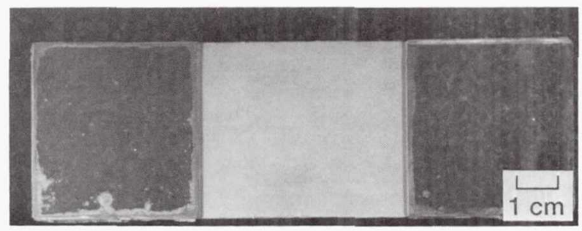
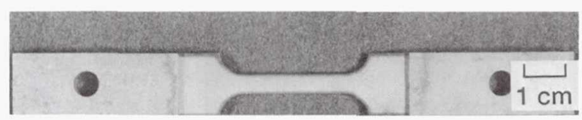


Figure 6.—Side view of HIP configuration.



(a) Consolidated panel.



(b) Test specimen.

Figure 7.—HIP consolidated panel and test specimen.

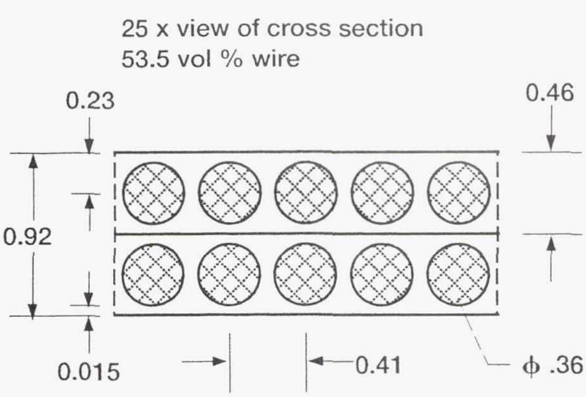


Figure 5.—Refractory metal wire reinforced superalloy composite panel design. Dimensions in mm.

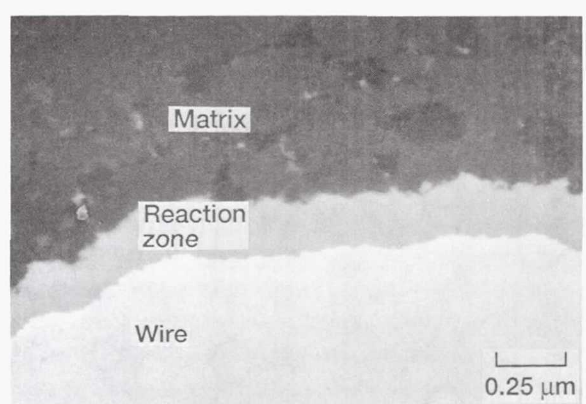


Figure 8.—W218/Waspaloy reaction zone.

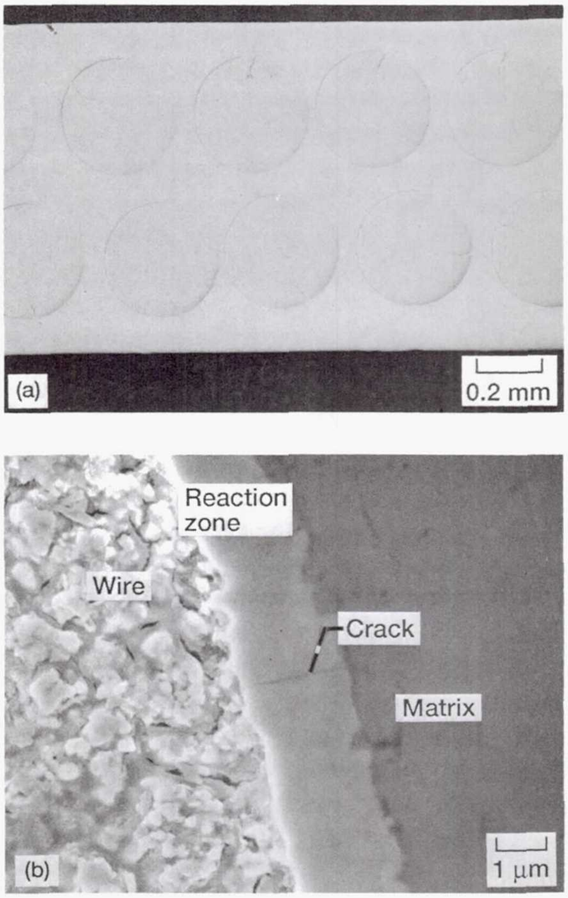


Figure 9.—W-24Re-HfC/Waspaloy composite.

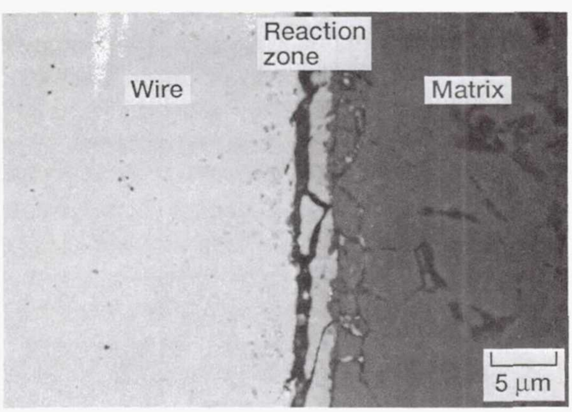


Figure 10.—Cracked μ phase in W-24Re-HfC reinforced Waspaloy composite after 1080 °C/1 hr/AC + 843 °C/24 hr/AC + 760 °C 16 hr/AC heat treatment.

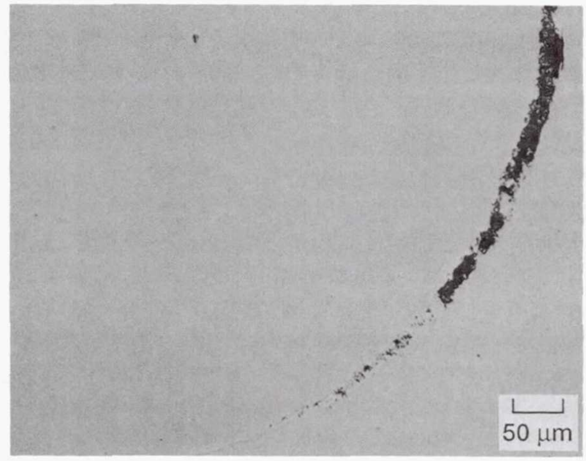
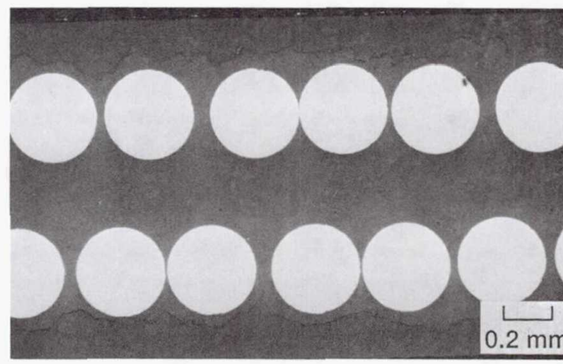
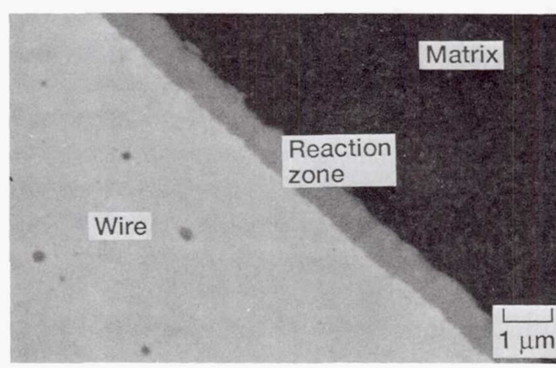


Figure 11.—Cracked W-24Re-HC reinforced Waspaloy reaction layer with diffusion sink deposition (W).



(a) General structure.



(b) Wire/matrix interface.

Figure 12.—W-24Re-HfC reinforced Waspaloy HIPed at 70 °C lower temperature.

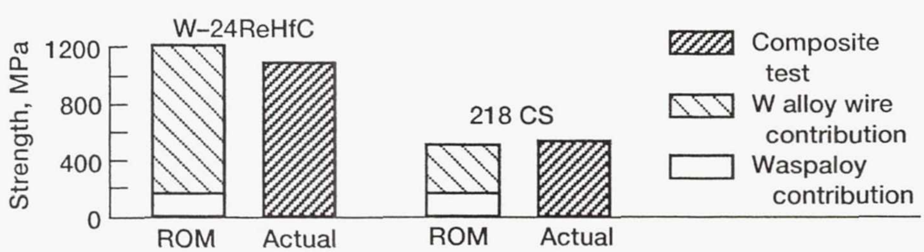


Figure 13.—Actual strength of 50 v/o wire composites compared to rule-of-mixtures predictions at 870 °C.

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