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FEASIBILITY OF PRODUCING CAST-REFRACTORY-METAL-FIBER-SUPERALLOY COMPOSITES

by Ruluff D. McIntyre
Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

A study was conducted to evaluate the feasibility of direct casting as a practical method for producing cast superalloy tungsten or columbium-alloy fiber composites while retaining a high percentage of fiber strength. Fourteen nickel-base, four cobalt, and three iron-based matrices were surveyed for degree of reaction with the metal fibers. Some stress-rupture results were obtained at temperatures of 760°, 816°, 871°, and 1093° C for a few composite systems. The feasibility of producing acceptable composites of some cast nickel, cobalt, and iron matrix alloys with tungsten or columbium alloy fibers was demonstrated.

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FEASIBILITY OF PRODUCING CAST-REFRACTORY-METAL-FIBER-SUPERALLOY COMPOSITES

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SUMMARY

A study was conducted to evaluate the feasibility of direct casting as a practical method of combining small diameter tungsten or columbium-alloy fibers with superalloy matrix materials while retaining a high percentage of fiber strength. The evaluation included metallographic analysis of fiber-matrix compatibility as well as stress-rupture testing of some representative as-cast matrix and composite materials at intermediate and high temperatures.

The study indicated the feasibility of using direct casting of nickel, cobalt, and iron alloys at 1620° C in air as a means of incorporating tungsten and columbium-alloy fibers to form acceptable cast composites. Matrix composition was identified as an important factor governing compatibility in the direct casting approach. When little reaction occurred, a significant percentage of fiber strength was retained during stress-rupture testing. For example, metallurgical observations indicated that at least one nickel alloy (in wt. %) (64Ni-15.5Cr-5.2Mo-10Fe-2Ti-3Al-0.15C-0.06B) and one cobalt alloy (56Co-16.7Cr-25W-3.7Cb) were compatible with small diameter 0.13-millimeter tungsten fibers. One-hundred-hour rupture data at 816° C for that nickel or cobalt matrix system showed no tungsten fiber strength loss. Stress-rupture data from 1093° C tests showed that only 20 percent of the tungsten fiber strength was lost.

INTRODUCTION

Refractory-metal fiber reinforcement can be a valuable approach for increasing the high temperature strength of superalloys (ref. 1), especially if small diameter, very high strength fibers can be used (ref. 2). Attempts have been made to fabricate such composites by direct casting (refs. 2 and 3). However, contact with the molten superalloy generally led to fiber dissolution, matrix-fiber interdiffusion, and recrystallization of small diameter, heavily worked fibers (e.g., diameters around 0.13 mm). These factors made the fibers ineffective for reinforcement. Thus, the common way to make high-temperature superalloy composites today is by powder metallurgical techniques involving solid-state sintering at temperatures considerably below the matrix melting temperature. However, since the direct casting approach offers some obvious advantages in cost and in process simplification, it was felt that this approach merited additional study.

The purpose of this study was to investigate the feasibility of direct casting as a practical means of incorporating metal fibers such as small diameter tungsten or columbium-alloy fibers into a superalloy matrix so as to produce acceptable cast composites. This was done by determining the influence of a low mold preheat casting technique and matrix compositional changes on the extent of fiber-matrix interaction. Specifically, 30 volume percent of 0.13-millimeter-diameter tungsten fibers and 1.3-millimeter-diameter columbium alloy FS-85 fibers were selected for incorporation primarily in nickel superalloy matrices. More reaction with the matrix was expected with columbium-alloy fibers so a larger diameter fiber was selected. The fibers selected were chosen to explore feasibility in anticipation of the availability of much higher strength tungsten and columbium-alloy fibers then under development. Limited studies were also conducted using cobalt and iron matrix alloys.

The fiber-matrix compatibility was evaluated primarily by metallographic techniques. In addition, for tungsten fibers only, measurements were made of the stress-rupture strengths of the superalloy matrix materials, with and without fiber reinforcement, at temperatures ranging from 760° to 1093° C. Also, in selected cases previous data on the rupture strengths of the tungsten fibers alone were used to provide an index of their degradation in the matrix. The FS-85 columbium alloy fibers were too weak to justify such strength measurements although some metallographic data were obtained.

MATERIALS AND PROCEDURE

Matrix Materials

Nickel-, cobalt-, and iron-base alloy materials were used in this investigation. The alloys were cast from the starting materials listed in table I. Most of the nominal matrix alloy compositions in table I conform to conventional, high strength superalloys. In some cases the amounts of refractory metal or more reactive elements were altered to explore their influence on strength and compatibility. Also shown in table I are the matrix alloy densities and as-cast compatibility of the alloys with the fibers.

Fiber Materials

The tungsten fibers (0.13 mm diam) were used in the as-drawn condition. A typical analysis in weight percent is aluminum, 0.001; calcium, 0.001; molybdenum, 0.002; copper, 0.001; with the balance being tungsten. Silicon, iron, chromium, nickel, manganese, tin, cobalt, silver, lead, thorium, and zirconium were all less than 0.001 weight percent in tungsten.

The FS-85 columbium-alloy fibers used were 1.3 millimeters in diameter with the following typical analysis: tantalum, 28.0; tungsten, 10.0; zirconium, 1.0; carbon, 0.031; oxygen, 0.044; nitrogen, 0.0047; columbium, the balance. These were also used in the as-drawn condition.

Specimen Fabrication

The matrix alloys were mixed from the elemental materials of the composition during melting just before casting. Two-pound melts were used. Figure 1 shows the fabrication technique for making test bar composites. The process is basically an investment casting technique. Wax test bar forms were surrounded with plaster molding material. The wax was vaporized in a furnace as the mold material was dried. A superalloy matrix material was induction heated to 1620° C in a zirconia crucible and poured into the mold, which was preheated to 650° C, immediately after the injection of fibers and removal of the tubes. The tubes contained enough fibers to make up 30 volume percent of a cast composite. Four test bars could be cast simultaneously from each mold. After casting, the mold containing the composites was cooled in air. Once cool, the bars were cut free of the assembly. The test bars were used for stress-rupture testing and microstructural analysis in the as-cast condition.

Mechanical Property Testing

Stress-rupture tests on cast matrix alloy specimens and on composite test specimens were conducted in conventional creep machines using helium atmospheres. Tests were conducted at 760°, 816°, 871°, or 1093° C. Test specimens had a 32-millimeter gage length, a 32-square-millimeter cross-sectional area, and measured 6.4 millimeters in diameter within the gage length.

Metallographic Studies

Microstructures of composites after casting and stress-rupture testing were obtained to examine fiber distribution and to evaluate compatibility. In particular, a careful inspection of the fiber-matrix interface was made to estimate the nature and degree of reaction of a fiber with the matrix. Metallographic specimens were cut from cast test bars approximately 6.4 millimeters from the center of the gage length. Specimens were mounted, polished, and photographed at ×100 or ×250. For the nickel-base, cobalt-base, and iron-base matrices an electrolytic - 10 percent chromic acid etch was used. For the tungsten fibers a caustic-ferricyanide etch was used (50 percent of a 30 percent ferricyanide solution and 50 percent of a 10 percent sodium hydroxide solution). For the FS-85 columbium-alloy fibers a 30 percent nitric acid - 10 percent hydrofluoric acid-60 percent water-etch was used.

RESULTS AND DISCUSSION

Compatibility

Table I shows the nominal compositions of the 21 matrix alloys that were tested for compatibility with 0.13-millimeter tungsten fibers and 1.3-millimeter FS-85 columbium-alloy fibers. Of the compositions surveyed, 14 were nickel-base alloys, four were cobalt-base, and three were iron-base. Table I also shows the as-cast compatibility, or lack of reaction, of the matrix alloys with the columbium alloy or tungsten fibers. In general, compatibility in the nickel matrices appeared to be better for compositions having more than 16 weight percent chromium and refractory metals and less than 3 weight percent aluminum (with the exception of alloy 4). Compatibility in cobalt and iron matrices also appeared to improve with higher amounts of chromium and refractory metal additions, although a systematic study would be needed to confirm these observations. Two alloys were compatible with both columbium alloy and tungsten fibers in the casting process. A compatible alloy is an alloy that produced little recrystallization and no dissolution of the fibers when viewed at ×100 or ×250. The most compatible alloys in weight percent were alloy 1 (64Ni-15.5Cr-5.25Mo-2Ti-3Al-0.15C-0.06B-10Fe) and alloy 15 (54.6Co-16.7Cr-25W-3.7Cb). Iron-base alloy 19 (69Fe-22Cr-5Ni-1W-1Mo-1Cb-1C-0.003B) was not as compatible as the best nickel-base or cobalt-base alloys, but it is promising. Alloy 7 (59.8Ni-9Cr-10Co-10W-2.5Mo-1.5Ti-5.5Al-0.05Zr-0.15C-0.015B) is an example of a high strength nickel-base alloy that showed poor compatibility for columbium-alloy fibers and only fair compatibility for tungsten fibers. Note that alloy 7 was high in aluminum and low in chromium. The other alloys showed generally poor to fair compatibility with the fibers. In many cases the fibers dissolved completely. The tungsten fibers were usually more resistant to dissolution than the FS-85 fibers.

Figure 2 shows the as-cast microstructures of typical composites made with the tungsten fibers or the FS-85 columbium-alloy fibers. The composites shown in figures 2(a) and (b) were made with nickel-base alloy 1 (table I), 2(c) and (d) with nickel-base alloy 7, 2(e) and (f) with cobalt-base alloy 15, and 2(g) and (h) with iron-base alloy 19. Figure 3 shows typical microstructures of composites after stress-rupture testing for approximately 100 hours at 1093° C. Figure 3(a) shows 0.13-millimeter-diameter tungsten fibers in nickel-base alloy 1. Figure 3(b) shows tungsten fibers in cobalt-base alloy 15. Figure 3(c) shows tungsten fibers in nickel-base alloy 7. And 3(d) shows 1.3-millimeter-diameter FS-85 columbium-alloy fibers in cobalt-base alloy 15. With the excellent compatibility of matrix alloys 1 and 15, significant strength improvements from fibers could be expected. The poor compatibility with matrix 7 would be expected to be associated with lower contributions to composite strength.

Stress-Rupture Properties

Stress-rupture test data including reduction-in-area values for the matrix alloys and some tungsten fiber reinforced composite materials appear in tables II and III, respectively. With the exception of alloy 7, strength data were not obtained for composites that showed severe reactions. Also, columbium-fiber-reinforced-composite strength data were not obtained because of the low wire properties. However, the excellent compatibility results obtained for some matrix alloys with columbium fibers suggests that high-strength composites might be fabricated if high-strength columbium wire were available. Tables IV and V offer 100-hour rupture-strength values for selected matrix materials and composites. These values were obtained by interpolation of the data from tables II and III. The 100-hour rupture strengths of the matrix alloys at 816° C fell within the normal range for conventional superalloys at that temperature. Rupture strengths for the matrix alloys ran from 138 to 440 meganewtons per square meter while conventional superalloys range from 69 to 593 meganewtons per square meter at 816° C. Comparison of tables IV and V shows that by adding 30 volume percent tungsten fibers to compatible nickel-base alloy 1 or cobalt-base alloy 15, the 100-hour rupture strength of the composites increased over that of the matrix at all test temperatures. Nickel-base alloy 7 had only fair compatibility with the tungsten fibers. The composite made with alloy 7 was stronger than the matrix alone at both 760° and 1093° C, but it was weaker at the intermediate temperatures, which is probably due to embrittled fibers.

Figure 4 compares the calculated 100-hour rupture strengths at 816° and 1093° C of the tungsten fibers in the composites (computed by the rule of mixtures) with the strengths of the same type of as-received (not subjected to casting) fibers measured alone under vacuum (ref. 4). The strengths of the fibers in the compatible matrices are at least equal to those of the vacuum tested fibers at 816° C and were about 80 percent as strong at 1093° C. As expected, figure 4(c) shows that in the case of alloy 7; when considerable fiber-matrix interaction occurs, the fibers in the matrix are weakened.

Figure 5 shows that, even with the relatively low strength fibers used in this study, on a 100-hour rupture strength-density-ratio basis, the unoptimized 30-volume-percent tungsten-fiber composites (no special heat treatments employed) made with nickel alloy 1 and cobalt alloy 15 were equal to or slightly less strong than the best conventional, optimized superalloys at 1093° C. This figure also shows strength-density ratio calculations for 70 volume percent fiber composites (such composites have been cast by this technique but not tested at Lewis). At the 70 volume percent level, compatible composites would clearly exceed the strength-density ratios of the best superalloys. Similar improvements could be expected by the incorporation of stronger fibers and fiber diameter optimization.

Figure 6 shows rupture curves at 816° and 1093° C, respectively, for the composites and matrix materials shown to have the best compatibility with tungsten wires. Although the main comparison of strength was based on 100-hour rupture strength, the longer time rupture data (table III and fig. 6(a)) indicate that, at least at 816° C, long time exposures do not cause a marked change in rupture behavior. Figure 6(b) shows that data for alloys 1 and 15 fall on about the same curve when reinforced. Comparative data for the matrix alloys alone, for one of the strongest nickel-base alloys (NASA-TRW-VIA) and for one of the strongest cobalt-base alloys (MM509) are also shown in figure 6(b) (refs. 5 to 7).

The metallographic data of figures 2(a), (c), and (e) and figure 3(a) to (c) help explain the strength comparisons. The tungsten fibers in nickel-base alloy 1 and cobalt-base alloy 15 show little attack after casting (figs. 2(a) and (e)), while the fibers in nickel-base alloy 7 show a diffusion zone and a loss of cold-worked structure (fig. 2(c)). At 1093° C after approximately 100 hours of rupture testing, the differences in degree of fiber degradation become very evident. The micrograph of cobalt-base alloy 15 still shows that much of the tungsten fibers are unreacted. Even the columbium-base alloy fiber (FS-85) has only a very small reaction zone (fig. 3(d)). Although the tungsten fibers in nickel-base alloy 1 show that some diffusion and attack has occurred after the 100-hour rupture testing at 1093° C, the degree of attack is much more severe in nickel-base alloy 7 (figs. 3(a) and (c)). The severity of the matrix reaction appears to be directly related to the amount of retained fiber strength: the greater the severity of reaction, the weaker the fibers in the composite. Figures 2(g) and (h) indicate that the iron-base alloy 19 (table I) has good compatibility for the tungsten and columbium-alloy fibers tested immediately after casting. It may be that composites strong in stress rupture could be made from iron-base alloy 19, also.

SUMMARY OF RESULTS

A study was conducted to evaluate the feasibility of direct casting as a practical method of combining small diameter tungsten or columbium-alloy fibers with superalloy matrix materials while retaining a high percentage of fiber strength. Evaluation included metallographic analysis of fiber-matrix compatibility as well as stress-rupture testing of some representative as-cast matrix and composite materials at intermediate and high temperatures.

The study indicated the feasibility of using direct casting of nickel, cobalt, and iron alloys at 1620° C in air as a means of incorporating tungsten and columbium-alloy fibers into a composite. The study showed that matrix composition is an important factor in the direct casting approach to refractory-metal-fiber superalloy-composite fabrication. Higher chromium and refractory metal contents appeared beneficial in all the matrix alloys evaluated (Ni, Co, and Fe base), and low aluminum contents appeared beneficial in nickel alloys. When little reaction occurs, a significant percentage of fiber strength is retained during stress-rupture testing. For example, at least one nickel alloy (64Ni-15.5Cr-5.2Mo-10Fe-2Ti-3Al-0.15C-0.06B) and one cobalt alloy (56Co-16.7Cr-25W-3.7Cb) were compatible with small diameter 0.13-millimeter tungsten fibers based on metallurgical observations. One-hundred-hour rupture data at 816° C for that nickel or cobalt matrix system showed no fiber strength loss and 1093° C rupture tests showed that only 20 percent of the fiber strength was lost.

CONCLUDING REMARKS

This study has shown that by proper selection of melt chemistry and casting conditions, molten superalloys will cause only minimal attack on 0.13-millimeter-diameter tungsten fibers or 1.3-millimeter-diameter FS-85 columbium-alloy fibers during the direct casting of fiber-superalloy composites. Also, subsequent high-temperature exposure (at least to 100 hr at 1093° C and to 1000 hr at 816° C) of compatible systems produces little to no loss in fiber strength. Thus, as very high-strength refractory-metal fibers are developed, improved superalloy composites may become feasible through a slightly modified direct casting technique.

Fiber incompatibility with the molten superalloy may also lead to improved superalloy composites. Here, fiber dissolution could be used selectively to directionally enrich the superalloy in strengthening elements in areas of critical stress. The superalloy matrix composition could then be chosen primarily for environmental resistance. Similar directional benefits might be envisioned if rapidly dissolving fibers can be made that incorporate carbide, oxide, or intermetallic strengthening phases.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 9, 1973,
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TABLE I. - NOMINAL COMPOSITION OF MATRIX ALLOYS AND

AS-CAST COMPATIBILITY WITH FIBERS

Alloy number	Nominal composition, weight percent													Density, g/cm^3	Compatibility[a] with fibers	
	Ni	Cr	Co	W	Mo	Ta	Cb	Ti	Al	Zr	C	B	Fe		FS-85	Tungsten
Nickel base																
1	64	15.5	----	----	5.25	---	----	2	3	----	0.15	0.06	10	7.83	Excellent	Excellent
2	54.5	13.1	----	15	4.5	---	----	1.7	2.5	----	.13	.051	8.5	8.66	Fair	Fair
3	41	18	18	18	----	---	----	2.5	2.5	----	----	-----	----	8.66	Fair	Fair
4	59	18	18	----	----	---	----	2.5	2.5	----	----	-----	----	7.92	Poor	Poor
5	60	6	10	8.5	1	6	2	2	4.5	----	----	-----	----	8.39	Poor	Poor
6	71.3	5.7	----	11	2	3	----	----	6.3	0.6	.13	-----	----	8.19	Poor	Poor
7	59.8	9	10	10	2.5	1.5	----	1.5	5.5	.05	.15	.015	----	8.08	Poor	Fair
8	59	14	----	5.1	4.9	2.9	----	1.9	2.8	----	----	-----	9.3	8.25	Fair	Fair
9	73.3	----	----	18.5	----	---	----	----	6.5	1.5	.15	-----	----	8.41	Poor	Fair
10	50	12.2	9	9	4.2	1.7	----	1.6	4.1	.09	.26	.18	7.9	8.14	Poor	Fair
11	58.8	10	10	10	----	3	----	1.5	5.5	1	.15	.015	----	8.05	Poor	Fair
12	60.3	9	10	12.5	----	---	1	2	5	.05	.15	.015	----	8.14	Poor	Fair
13	61.7	10.3	10	9	----	---	1.5	1	6.3	.1	.11	.03	----	7.86	Poor	Fair
14	64.8	8	10	----	6	4	----	1	6	.1	.1	.015	----	7.78	Poor	Fair
Cobalt base																
15	----	16.7	54.6	25	----	---	3.7	----	---	----	----	-----	----	9.74	Excellent	Excellent
16	----	18	60.3	18	----	---	3.7	----	---	----	----	-----	----	9.41	Fair	Fair
17	----	21.5	61	9	----	4.5	----	0.75	---	2.25	1	-----	----	8.66	Poor	Poor
18	27	19	36	12	----	2	----	3.8	---	----	.2	0.02	----	8.77	Poor	Poor
Iron base																
19	5	22	----	1	1	---	1	----	---	----	1	0.003	69	7.64	Good	Good
20	4	17	----	----	----	---	.25	----	---	----	.04	-----	78.7	7.78	Poor	Poor
21	12	17	----	----	2.5	---	----	----	---	----	.08	-----	68.4	7.89	Poor	Poor

[a]Compatibility code: Excellent, little to no recrystallization; good, some recrystallization; fair, recrystallization plus dissolution; poor, dissolution.

TABLE II. - STRESS-RUPTURE PROPERTIES OF MATRIX

MATERIALS WITHOUT FIBERS

Alloy number	Temperature, °C	Stress, MN/m^2	Life, hr	Reduction in area, percent
1	760	207	29.2	9.2
		172	66.4	6.2
		172	57.0	13.2
		144	416.0	22.6
		141	284.0	64.2
		165	106.0	4.3
	816	255	1.9	39.7
		179	19.7	26.4
		138	84.4	31.7
	871	207	1.1	10.3
		97	108.0	3.1
	1093	20.7	86.2	1.6
		13.8	166.0	.84
		13.8	187.0	6.9
2	816	255	5.9	16.7
		227	15.2	16.7
		172	77.9	17.8
5	816	276	80.1	6.2
		379	4.6	5.3
6	816	379	68.0	0.85
		345	256.0	6.6
7	760	565	95.9	2.3
		565	156.0	2.3
		648	155.0	4.5
	816	441	95.2	8.0
		441	26.6	3.9
		393	400.0	2.4
		448	256.0	3.0
	871	414	85.8	8.0
		393	86.1	2.8
		414	32.2	7.5
		379	110.0	4.3
	1093	27.6	170.6	0
		24.1	291	2.5
		31.0	92.3	1.6
8	760	255	51.0	27.0
	816	141	161.0	20.9
	871	207	2.0	28.0
9	816	276	252	3.8
	871	276	44	0
10	816	276	13.8	1.6
		276	4.6	3.5
11	760	535	67.3	0
	816	276	45.4	2.7
12	816	414	84.5	4.2
	871	414	36.0	0
13	816	414	101.3	0
14	816	379	354	0
		379	105.3	3
	871	345	80.8	0
15	760	331	102.3	3.0
		310	238.0	2.4
		296	376.0	20.8
		276	1152.0	3.9
	816	262	105.0	16.7
		255	170.0	1.6
		227	320.0	9.6
		200	516.0	6.8
	871	227	23.2	5.4
		207	122.0	14.7
		141	851.0	29.7
	1093	34.5	91.7	4.2
		34.5	46.6	4.5
		31.0	82.6	2.7
		27.6	233	1.6
		31.0	100.1	3.0
16	816	241	86.9	1.6
		207	189.0	10.3
		193	393.0	22.7
		172	853.0	6.2
17	816	276	31.6	0
18	816	310	1626.0	9.1
		276	84.5	34.0
19	760	200	1.4	14.2
	816	186	3.0	10.6
		110	68.6	6.5
20	816	89.6	0.6	15.6
		141	.03	8.4
21	760	103	8.4	14.5
	816	103	5.3	22.1

TABLE III. - STRESS-RUPTURE PROPERTIES OF 30-VOLUME-PERCENT

TUNGSTEN-FIBER COMPOSITES

Matrix alloy	Temperature, °C	Stress, MN/m^2	Life, hr	Reduction in area, percent
1	760	400	689.0	5.4
		379	1318.0	6.9
	816	414	66.0	8.8
		379	165.0	4.3
		345	539.0	5.8
		310	1001.0	6.2
	871	379	83.9	6.9
		345	340.0	21.0
	1093	114	94.3	5.4
		124	8.7	4.1
7	760	593	86.2	0
		503	360.0	7.5
	816	414	164.0	5.0
		393	325.0	7.4
		462	17.0	3.8
7	871	414	7.5	4.5
		393	63.4	3.4
		379	75.1	2.7
	1093	152	0.4	3.1
		114	1.4	3.4
		76	80.4	4.7
15	760	448	86.8	5.6
	816	462	24.8	11.0
		434	76.4	11.3
		400	251.0	21.1
		352	868.0	15.7
	871	338	772.0	19.5
		372	180.0	11.0
	1093	114	110.0	1.6
		124	5.1	4.7

TABLE IV. - 100-HOUR STRESS-RUPTURE PROPERTIES OF SELECTED MATRIX MATERIALS

Matrix alloy	Temperature, °C	Stress, MN/m^2
1	760	165
	816	138
	871	97
	1093	20.7
2	816	164
5	816	278
6	816	369
7	760	565
	816	440
	871	390
	1093	31
8	816	141
9	816	276
12	816	414
13	816	414
14	816	379
	871	345
15	760	331
	816	276
	871	207
	1093	31
16	816	241
19	816	74

TABLE V. - 100-HOUR STRESS-RUPTURE STRENGTH OF 30-VOLUME-PERCENT TUNGSTEN-FIBER COMPOSITES

Matrix alloy	Temperature, °C	Stress, MN/m^2
1	760	441
	816	400
	871	379
	1093	114
7	760	593
	816	427
	871	379
	1093	75
15	760	448
	816	434
	871	386
	1093	114

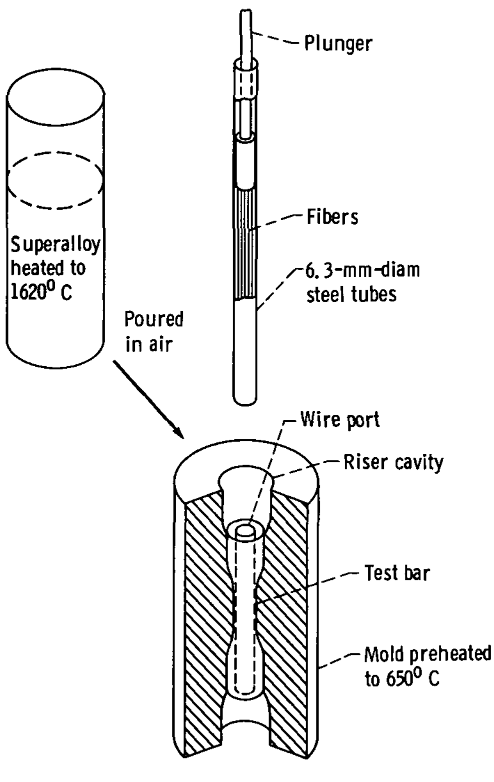
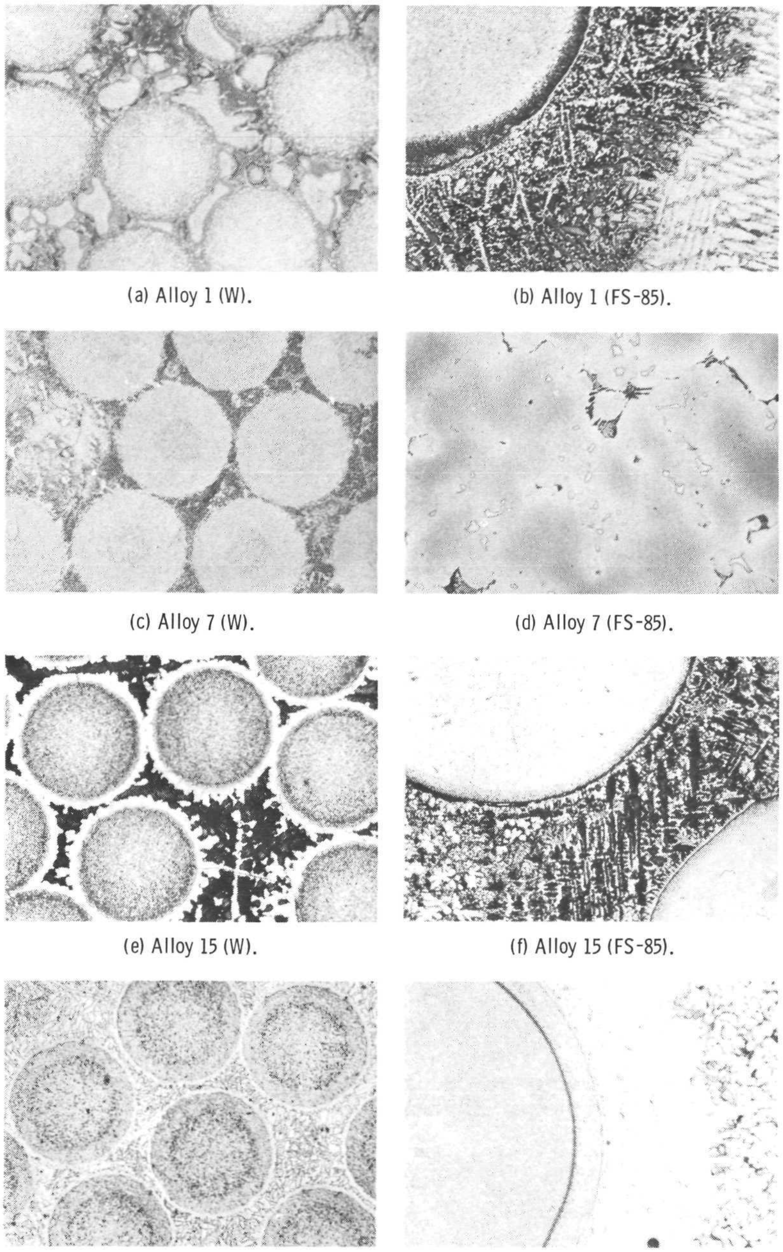


Figure 1. - Fabrication technique used for casting refractory metal fiber-superalloy matrix composites.



(a) Alloy 1 (W).

(b) Alloy 1 (FS-85).

(c) Alloy 7 (W).

(d) Alloy 7 (FS-85).

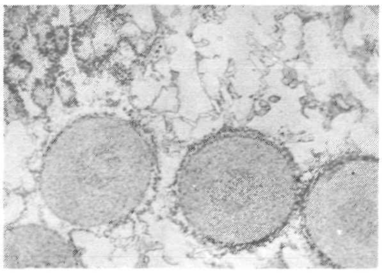
(e) Alloy 15 (W).

(f) Alloy 15 (FS-85).

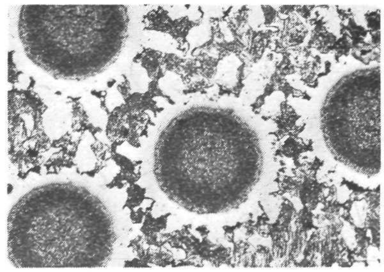
(g) Alloy 19 (W).

(h) Alloy 19 (FS-85).

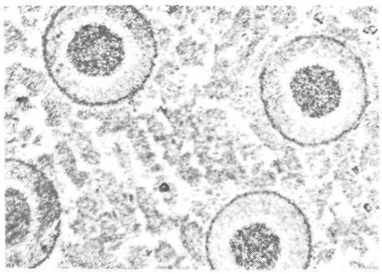
Figure 2. - Microstructures of as-cast composites containing 30 volume percent of 0.13-millimeter-diameter tungsten (W) fibers or 1.3-millimeter-diameter columbium-alloy (FS-85) fibers in various alloy matrices. Tungsten fibers at X250; FS-85 fibers at X100. Reduced 50 percent in printing.



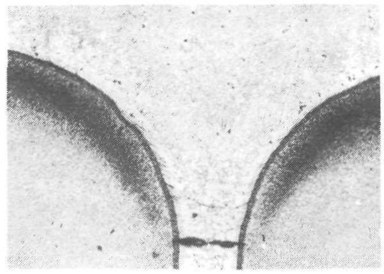
(a) Alloy 1 (W).



(b) Alloy 15 (W).



(c) Alloy 7 (W).



(d) Alloy 15 (FS-85).

Figure 3. - Tungsten (W) and columbium-alloy (FS-85) fibers in composites after approximately 100 hours of stress-rupture testing at 1093° C. Tungsten fibers at X250; FS-85 fibers at X100. Reduced 50 percent in printing.

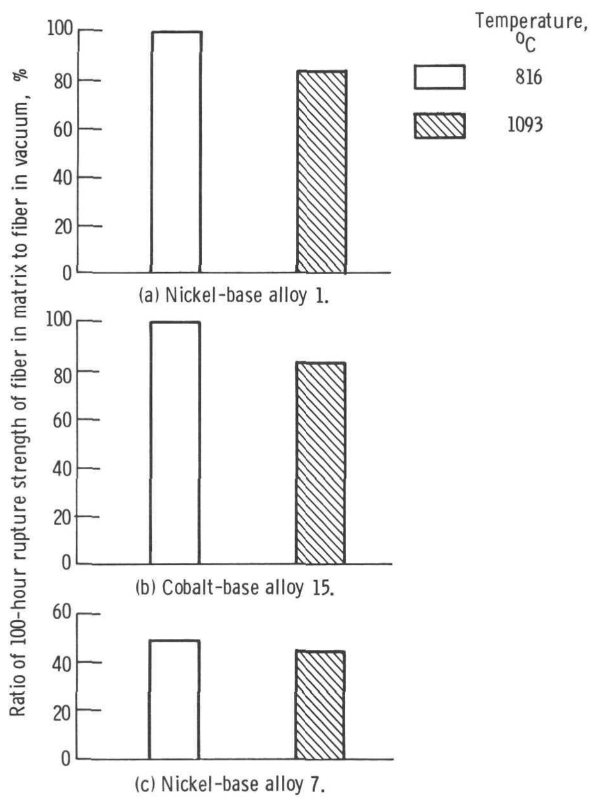


Figure 4. - Comparison of tungsten fiber 100-hour rupture strength when tested in matrix alloys with rupture strength of vacuum-tested fibers (ref. 4). Rupture strength of fiber matrix is computed by rule of mixtures from composite data.

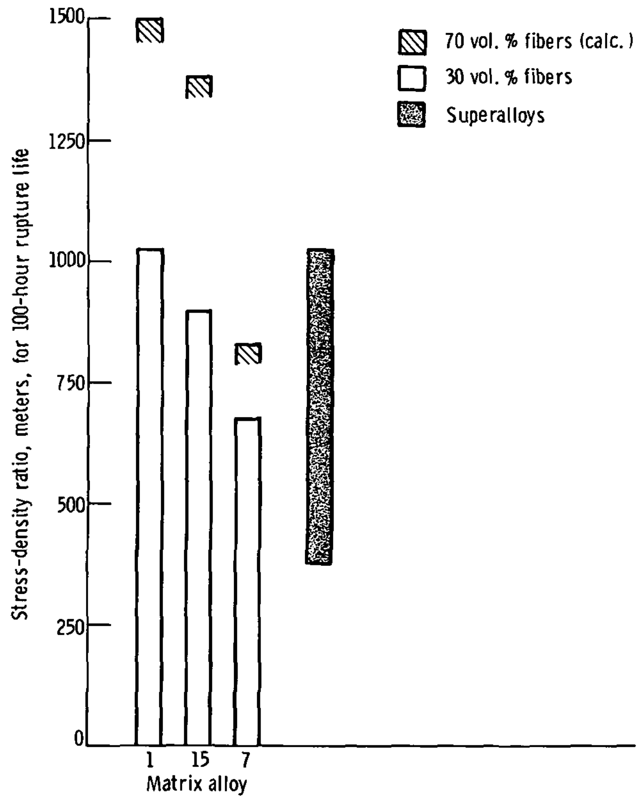


Figure 5. - 100-Hour rupture strength to density ratio of 30-volume-percent tungsten fiber composites at 1093° C compared with superalloys.

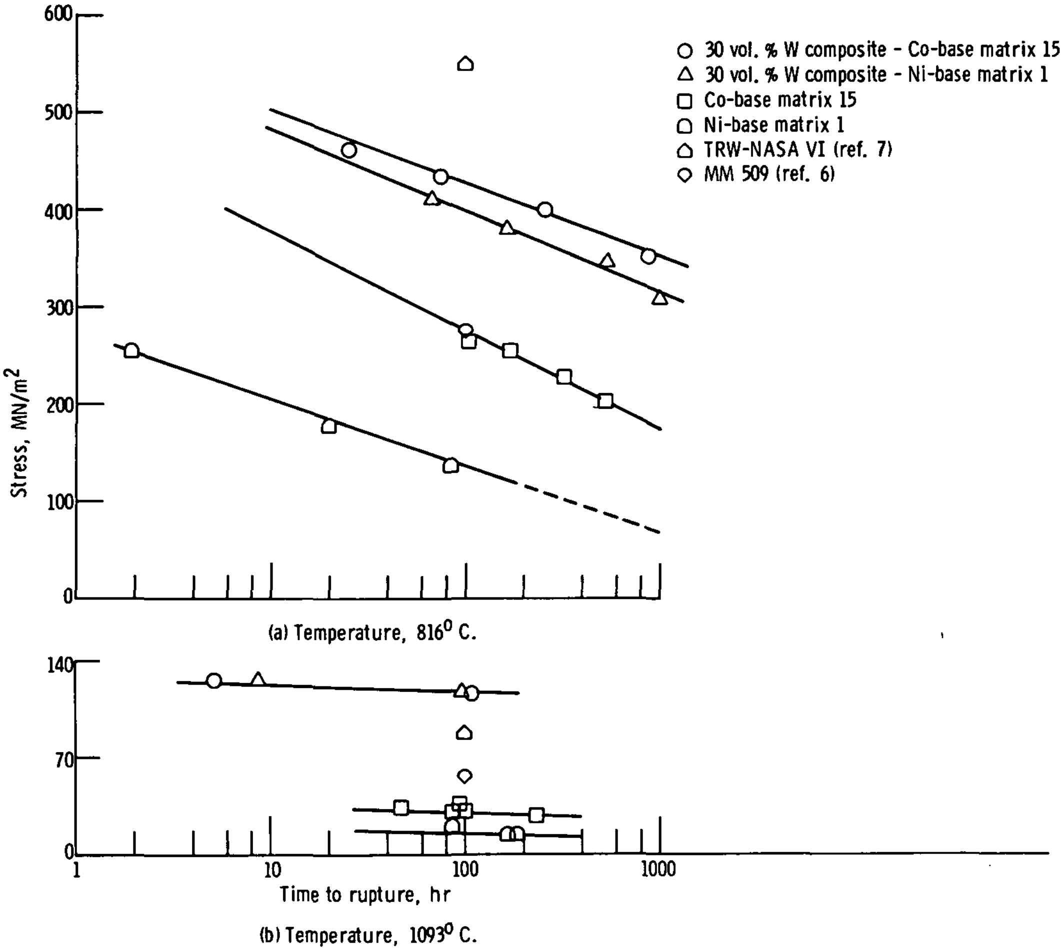


Figure 6. - Effect of stress on rupture life for 30-volume-percent tungsten fiber composites in nickel or cobalt base matrices.

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