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JUL 77 I AHMAD, J M BARRANCO

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REINFORCED COBALT ALLOY COMPOSITE FOR TURBINE BLADE APPLICATION

I. AHMAD
J.M. BARRANCO

July 1977

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
LARGE CALIBER WEAPON SYSTEM LABORATORY
BENÉT WEAPONS LABORATORY
WATERVLIET, N. Y. 12189

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A composite of 0.42 V_f W-2% ThO_2 filament reinforced cobalt base alloy has been developed. It can be fabricated by convential investment casting process, has a 1093°C (2000°F), 100hr. stress-to-rupture of 206MN/M2 (30Ksi) and a charpy impact strength of 280.0 in-lb at 835°C as compared with 20.6 in-lb for the unreinforced alloy. Also the feasibility of casting a prototype first stage blade of JT9D engine has been demonstrated.

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REINFORCED COBALT ALLOY COMPOSITE FOR TURBINE BLADE APPLICATION

by

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I. Ahmad and J. M. Barranco

ABSTRACT

A composite of 0.42 V_f W-2% ThO_2 filament reinforced cobalt base alloy has been developed. It can be fabricated by conventional investment casting process, has a 1093°C (2000°F), 100 hr. stress-to-rupture of 206 MN/M^2 (30 Ksi), and a charpy impact strength of 280.0 in-lb at 835°C as compared with 20.6 in-lb for the unreinforced alloy. Also the feasibility of casting a prototype first stage blade of JT9D engine has been demonstrated.

1. INTRODUCTION

Considerable improvements in the high temperature properties of superalloys have been achieved during the last twenty five years by using conventional metallurgical techniques of strengthening, such as solid solutioning, precipitation and dispersion hardening, grain refining and directional solidification, etc. However, with the advancement in the gas turbine technology the gap between the highest temperature at which these alloys can be used and the gas inlet temperatures for which the engines are being designed is progressively widening. For example, the best nickel base superalloy used for turbine blades can perform up to 1800°F and some of the directionally solidified eutectics alloys can be used up to 1900°F; however, the gas inlet temperatures in the advanced engines exceed 2300°F. This makes the air cooling of these components in the turbine section necessary, which means increased fuel consumption. Therefore, there is a strong need for materials which can withstand the design stresses in the blades at increasingly higher temperatures.

The potential of high temperature — high strength filament reinforced metal matrix composites to achieve materials with prerequisite properties is now well recognized. For turbine blade application some work on the reinforcement of superalloys has already been reported. For example, Ellison and Harris[1] have achieved improvement in the properties of IN600 by incorporating 76 micron (0.003") dia. tungsten wire using hot rolling technique. Dean[2] prepared 0.50 V_f composites of tungsten wires infiltrated with IN713C, a conventional nickel base alloy and showed that the composite had a 100 hr. stress-to-rupture of 130 MN/M^2 (19 Ksi) at 1093°C (2000°F).

Petrasek, et al using a slip casting - hot isotatic pressing technique fabricated composites of W-3%Re[3], W-2%ThO_2[4] and W-HfC[5] wires in a nickel base alloy matrix, and showed improvement of 2000°F stress-to-rupture in every case. Recently Brentnall has reported making W filament - FeCrA1Y alloy composites by high temperature diffusion bonding involving powder cloth technique[6].

The major objective of our study was to develop a com-

posite material for 1093°C (2000°F) service temperature, fabricable by the state of the art technology, which for the turbine blades is vacuum induction melting-investment casting. Cobalt base alloys were preferred as matrix material over nickel base alloys, because the former have higher m.p. (approximately 100°C) and have superior hot corrosion resistance. The plan was to develop the basic technology using an easily available filament such as W-2%ThO_2, which has reasonably good stress-to-rupture properties at 1100 - 1200°C (2000 - 2200°F), and then explore the use of low density filaments with more attractive properties, such as those of low density SiC or alpha Al_2O_3.

In this paper the process for the fabrication and high temperature properties of W-2%ThO_2 - cobalt alloy composites and results of preliminary efforts of casting composite blades will be described. Work on the reinforcement of superalloys with SiC filament is in progress and will be reported at a later date.

2. EXPERIMENTAL PROCEDURES AND RESULTS

Materials

W-2%ThO_2 filament 75 micron (.003") in diameter prepared by the powder metallurgical technique was obtained from Westinghouse, Bloomsfield, NJ in the straightened and chemically cleaned condition. The average (3 specimens) tensile strength* and reduction in area measured (vacuum) on a Tinius Olsen Machine are shown in Figure 1.

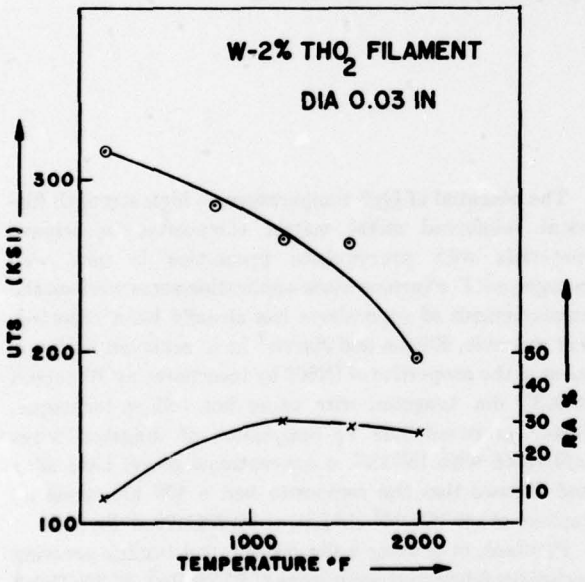


Figure 1. Tensile Properties of W-2ThO_2 Filament (.003" diameter) as a Function of Temperature.

* The variation in tensile strength in the same batch of the filament was ±10%.

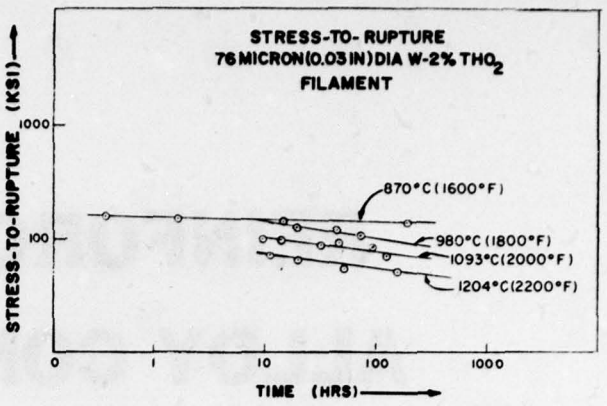
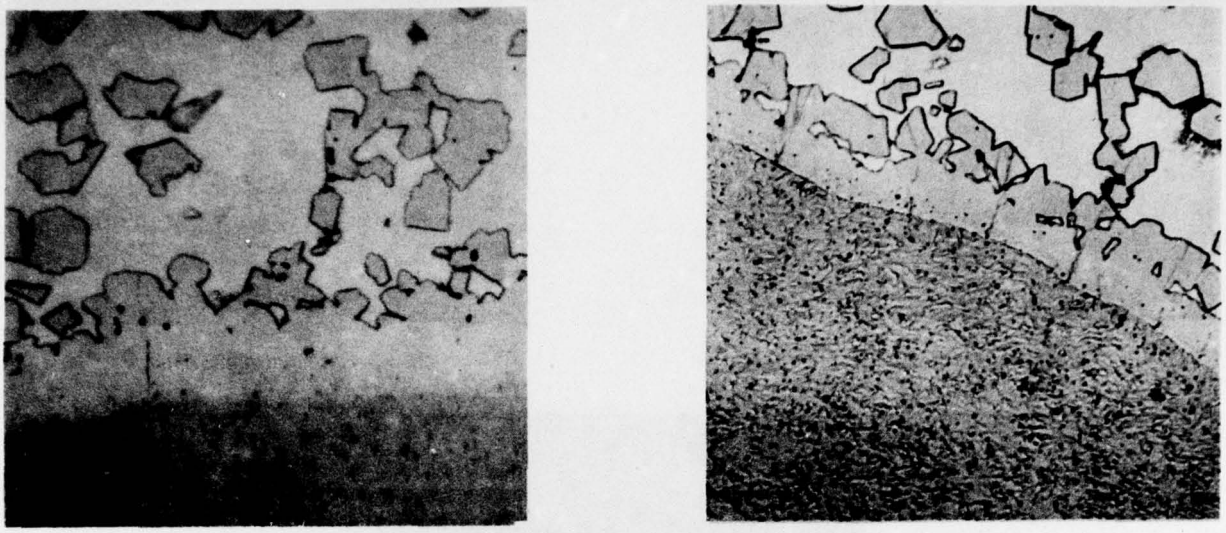


Figure 2. Stress Rupture Properties of W-2ThO_2 Filament 75 Micron (.003" diameter).

The filament had large die marks on the surface and in some cases longitudinal cracking was observed. The stress-to-rupture data at various temperature obtained in vacuum (Westinghouse) is shown in Figure 2 and summarized in Table 1.

TABLE I.
STRESS RUPTURE DATA OF W-2ThO_2 FILAMENT
75 MICRON (.003" IN DIA)

	STRESS MN/M²	(KSI)	TIME (HR)
870°C (1600°F)	1241	(180)	0.05
	1103	(160)	0.4
	1034	(150)	2
	965	(140)	15
	931	(135)	199
980°C (1800°F)	875	(127)	20
	779	(113)	46
	724	(105)	76
1093°C (2000°F)	690	(100)	10
	620	(90)	47
	607	(88)	33
	559	(81)	93
	524	(76)	118
	497	(72)	128
1205°C (2200°F)	482	(70)	12
	455	(66)	20
	379	(55)	54
	344	(50)	160



(a) 9% Tungsten

(b) 25% Tungsten. (x1000)

Figure 3. Reaction Zone of W-1ThO_2 Filament and Mar M322 Alloys.

Because of its high melting point, and high W content, cobalt base Mar M322 (1.0C, 21.5Cr, 9W, 0.75Ti, 4.5Ta, 20Zr) was selected as the basis for developing the matrix alloy. Initial compatibility runs made by infiltrating a bundle of wires with the molten alloy showed, that by increasing tungsten content in the alloy from 9 to 25%, the fil-matrix interaction could be reduced quite significantly. As shown in Figure 3, the interaction zone in a composite with matrix containing 25% W was only a few microns thick.

In the course of investigations on the composite casting parameters it also became evident that it was desirable to have better ductility in the matrix. Therefore, further modification was made in its composition by reducing carbon and adding 10% Ni. Also Zr was eliminated because it gave problems of the interaction of the melt with the mold material. The modified compositions investigated in this study and their designations are given in Table II. The

TABLE II.
COMPOSITION (WT%) AND DESIGNATION OF MODIFIED MAR M322 ALLOYS

Alloy	C	Cr	W	Ni	Ti	Ta	Zr
Mar M322 A (Standard)	1.0	21.5	9.0	—	0.75	4.5	1.5
Mar M322 B	1.0	21.5	20.0	—	0.75	4.5	—
Mar M322 C	1.0	21.5	25.0	—	0.75	4.5	—
Mar M322 D	0.75	21.5	25.0	10.0	0.75	4.5	—
Mar M322 E	0.30	21.5	25.0	10.0	0.75	3.5	—

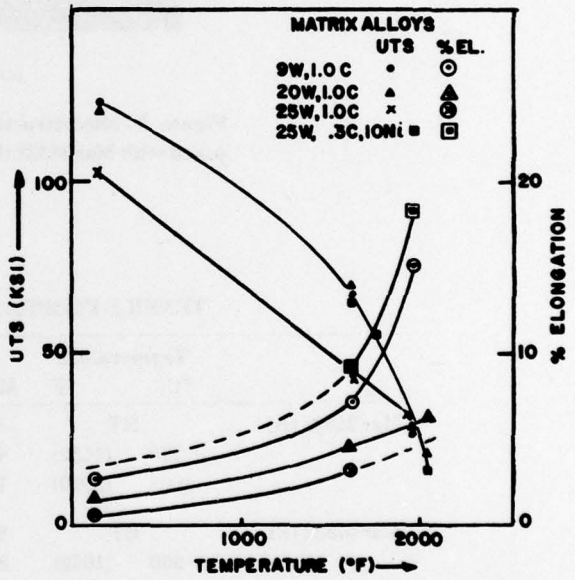
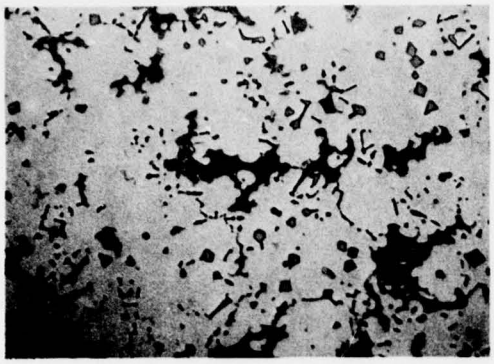
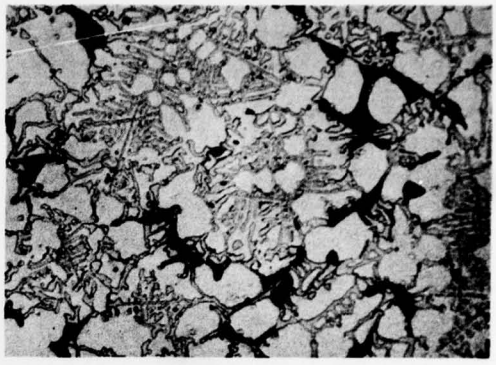


Figure 4. Tensile Properties of Matrix Alloys as a Function of Temperature.

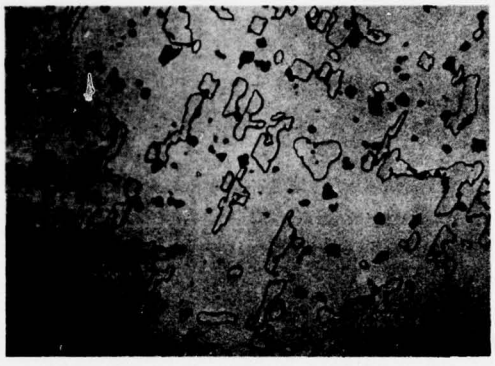
tensile strength and percent elongation of some of these alloys are summarized in Table III, and shown in Figure 4, which indicate that although the alloy containing 10% Ni and 0.3% C had the same tensile strength as the standard alloy, its ductility was superior. At 1093°C (2000°F) all the alloys had approximately the same tensile strength.



(a) Mar M322 (Standard)



(b) Mar M322 (D)



(c) Mar M322 (E)

Figure 5. Microstructures of Mar M322 Standard Compared with Mar M322 (D) and Mar M322 (E), (x2000)

TABLE III
TENSILE PROPERTIES OF THE MATRIX ALLOYS

	Temperature		UTS		YS		
	°C	°F	MN/M^2	Ksi	MN/M^2	Ksi	%el
Mar M322 (A)	RT		848	(123)	651	94.5	2.8
	900	(1652)	469	(68)	324	47	7.2
	1093	(2000)	193	(28)	165	24	15.1
Mar M322 (B)	RT		834	(121)	690	100	1.5
	900	(1652)	303	(44)	255	37	4.6
	1093	(2000)	200	(29)	193	28	18.7
Mar M322 (C)	RT		710	(103)	—	—	0.5
	1093	(2000)	214	(31)	214	31	3.6
Mar M322 (E)	RT		448	(65)	303	44	9
	900	(1652)	386	(56)	276	40	18
	980	(1800)	117	(17)	110	16	—

UTS = Ultimate tensile strength, YS = Yield strength, %el = Percent elongation.

The microstructure of the alloy with 0.3% C and 10% Ni showed a blocky carbide structure, which is more desirable as compared with the other two alloys which has large areas of cellular colonies, as shown in Figure 5.

Fabrication of the Composites

The conventional vacuum investment casting process was used to fabricate the tensile, charpy and thermal fatigue specimens, employing collodial silica as binder, zircon flour as the refractory and a mixture of zircon sand and alumino silicate aggregates as the stucco material. The molds were dewaxed using trichloroethylene vapor degreaser, followed by thoroughly rinsing with liquid trichloroethylene and air drying. They were fired at 1000°C in hydrogen. Further baking was accomplished under vacuum using conventional equipment. The charge was melted and solidified in vacuum a number of times for thorough mixing of the elements and degassing. The mold was heated to 1000 - 1050°C and baked for 1 hour before pouring the molten charge, which was at a 100 - 150°C superheat temperature. Tensile specimens were cast in the form of 1.27 cm (0.5 in) diameter and 9cm (3.5 in) long bars. For this the filament was cut into 10 cm lengths, bundled and centered in a specially designed mold in which molten wax was poured to encapsulate the filaments. There were four bars in each shell. To allow for the expansion of the filament during casting, about 3mm wax was provided on one end of the bundle. Similar technique was used to cast the thermal fatigue specimens and the charpy test bars. Figure 6 shows a sketch of the as-cast specimen tree.

The casting of a prototype first stage JT9D blade, was successfully accomplished using tapes of filaments held by means of a fugitive thermoplastic binder. These tapes were laid up in alloys, conforming to the airfoil shape which were then encapsulated in wax in the form of regular blade geometry with the root block attached (Figure 7a). Wax caps were placed over each end of the bundle to provide expansion space for tungsten filaments. This wax assembly

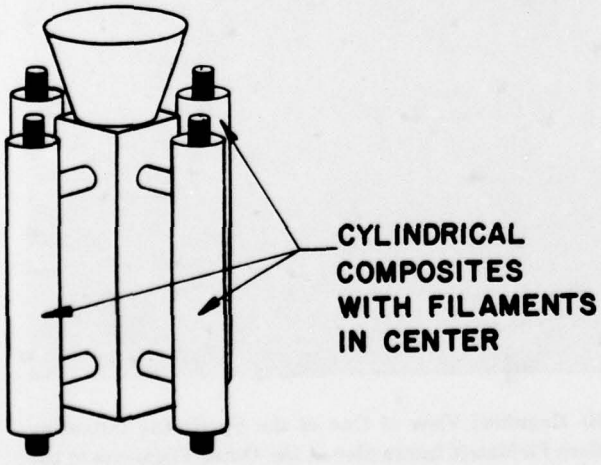
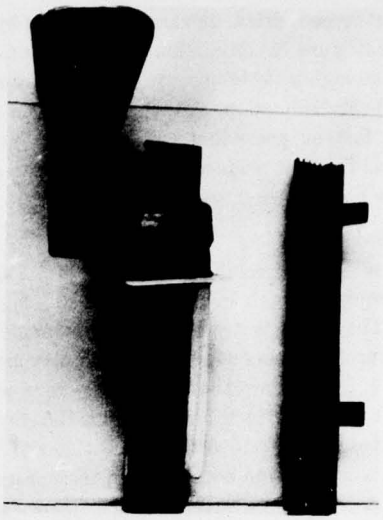
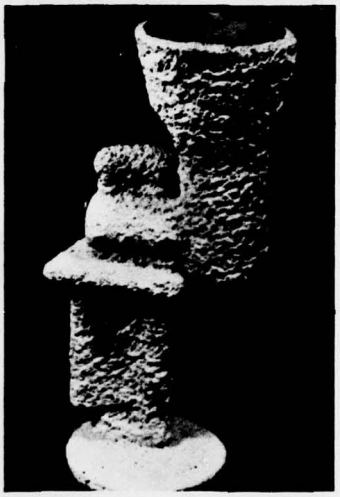


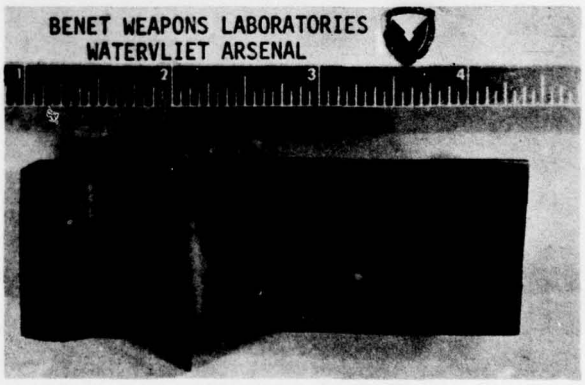
Figure 6. Sketch Showing the As Cast Tree of Composite Specimens.



(a) Positioning of Filament Tape in the Wax



(b) Shell Mold Prior to Casting.



(c) The Cast Blade after Trimming the Ends.

Figure 7. Sequence for Casting a Prototype Jet Engine Composite Turbine Blade.

was then stuccoed, dried, dewaxed and baked by the usual procedure (Figure 7b). Minimum pour temperature (1400 - 1450°C) and high mold temperature (1370°C) was found to give the best infiltration. After pouring, the mold was cooled as fast as possible to reduce filament - matrix interaction. The cast blade after cutting off the gates, etc. is shown in Figure 7c.

Test and Evaluation

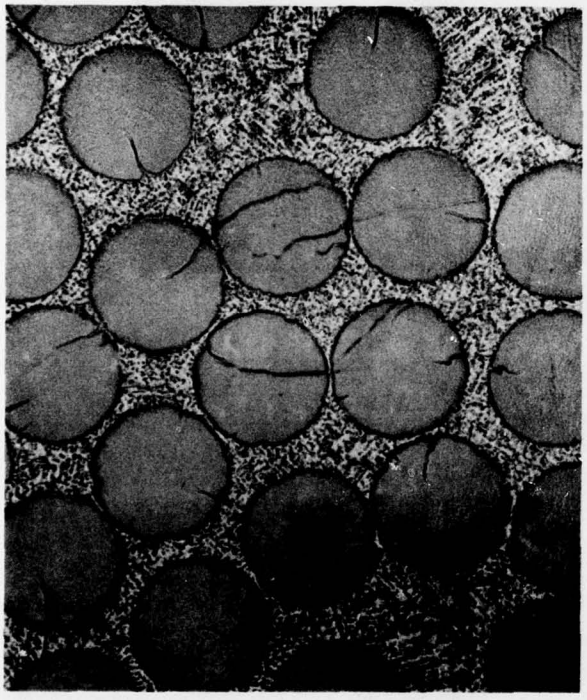
Tensile tests were conducted on a 20 Ksi Tinius Olsen Machine equipped with high temperature - high vacuum chamber. The stress-to-rupture tests were made on a 2500 Kg Satec machine using specimen design recommended in reference 7. Preliminary thermal fatigue runs were made on a Mach 0.3 burner rig at NASA Lewis Research Labs at temperatures 450 ⇆ 1093°C (800 ⇆ 2000°F). Charpy impact tests were made both at room temperature and at 835°C (1535°F). For the latter, the specimen was exposed in a furnace to slightly higher than the test temperature. In the short time taken for the transfer of the specimen from the furnace to the impact test machine (a few seconds), the temperature of the specimen fell to the required test temperature.

Further evaluation of the composites was made by metallographic examination, microprobe and x-ray diffraction analysis.

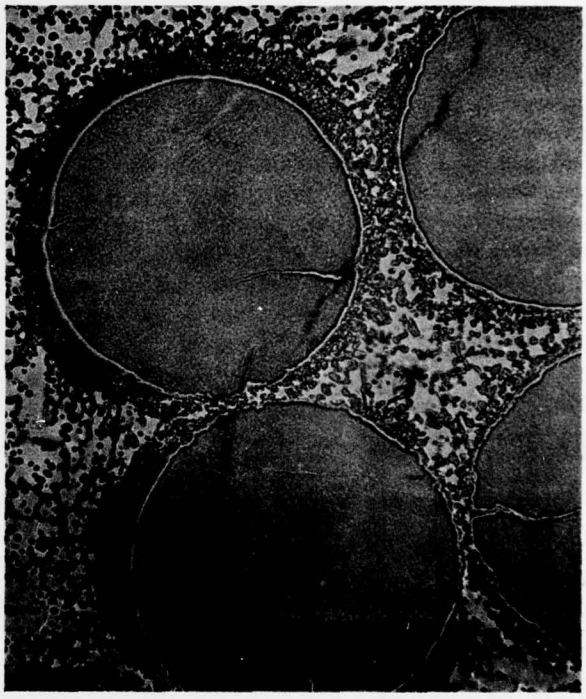
3. RESULTS

W-2%ThO_2 - Mar M322 (Modified) Composites

A number of parameters such as melt temperature, mold temperature and pressure during casting, etc. were optimized to obtain good infiltration with minimum interaction. In the facility used for casting the composite specimens, the maximum temperature to which the mold could be heated was 1050°C. Satisfactory infiltration with minimum filament-matrix interaction was observed using an optimum melt temperature which was found to be 1490°C. Monitoring the temperature of the filament during casting indicated the filament temperature increased to 1220°C, while the matrix cooled to 1260°C in about 10 minutes after pouring the melt. The transverse section of a typical specimen shows that the matrix infiltration was good, as indicated in Figure 8a. Some micrographs indicated that the outer filaments see higher temperatures than the inner filament in the bundle and the matrix composition inside of the bundle became richer in tungsten (Figure 8b).



(a) Fil-Matrix Interaction



(b) Magnified View of One of the Specimens Indicating More Fil-Matrix Interaction at the Outer Filaments in the Bundle.

Figure 8. Section of the W-2%ThO_2/Mar M322 (E) Composite

Tensile Properties

Table III summarizes the tensile and yield strengths of the composites with modified Mar M322 matrices. The room temperature value of all the composites was always lower than the matrix, most probably because of the brittleness of the fil-matrix interaction zone, which had some microcracks, such as shown in Figure 9. Also, at room temperature, W is brittle and sensitive to flaws. As has been mentioned earlier, the matrix at elevated temperatures shows considerable ductility. Composites with filament V_f lower than 0.25 also showed some ductility. Higher V_f composites fractured in a brittle manner even at elevated temperatures (Figure 10). The use of a more ductile matrix (Mar M322-E) slightly improved the ductility of the composite.

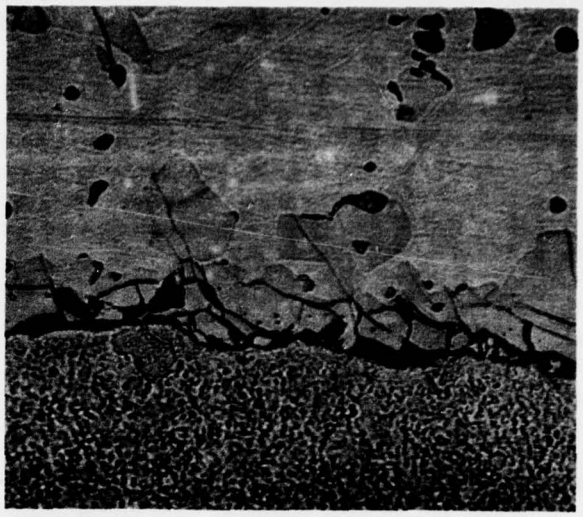
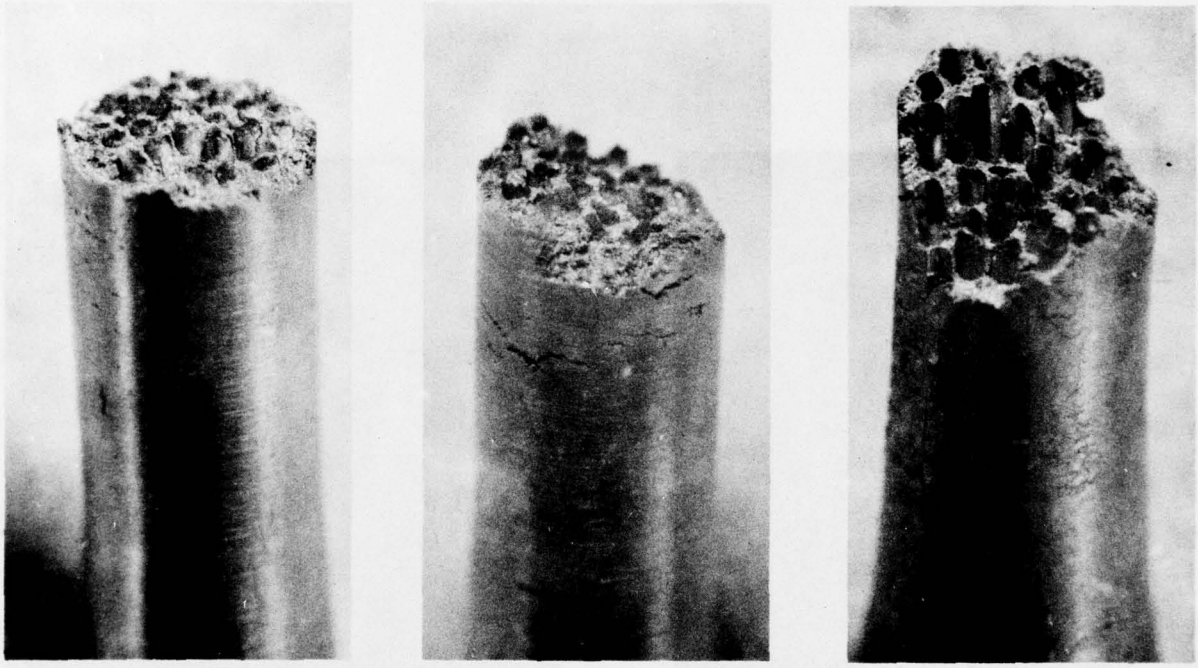


Figure 9. Filament - Matrix Interaction Zone Showing Microcracks. (x 1000)



(a) 1800F (b) 2000 F (c) 2100 F

Figure 10. Tensile Fractures of Composites at Elevated Temperatures (x5)

Stress-To-Rupture Values

The stress-to-rupture data are summarized in Table V and are plotted in Figure 11. The values for as cast matrix alloys are also plotted. It will be noticed that the alloy with high carbon (1.0C) is superior to the low carbon alloy.

Charpy Impact Strength

The charpy impact strength for the matrix and composites are given in Table VI. At room temperature, the matrix alloy and the composite fractured in a brittle manner, as shown in Figure 12a, but at 835°C (1535°F) the

fracture surface of the composite showed necking of the filament (Figure 12b); although the matrix still appeared to be relatively brittle.

Thermal Fatigue

Two specimens one blank and one with 0.17 V_f were exposed to 450 ⇆ 1093°C cycles for 500 times in the burner rig in which the specimens were aligned in a circular table, with the edge of the foil towards the flame. While the blank specimen did not dimensionally change after the test, the composite specimen warped as shown in Figure 13a. Examination of the transverse section of the specimen indicated a rachetting effect accompanied by some debonding of the filament from the matrix (Figure 13b). The microstructure of the matrix and the filament did not visibly change.

Long Period Filament Matrix Interaction

A number of composite specimens were sealed under vacuum in quartz capsules, and exposed to 1093°C

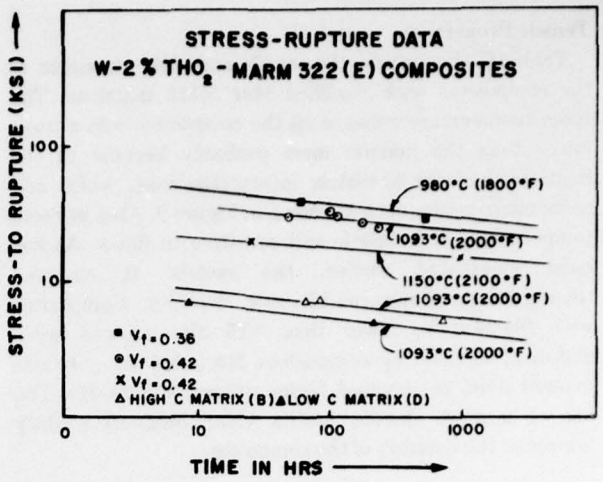
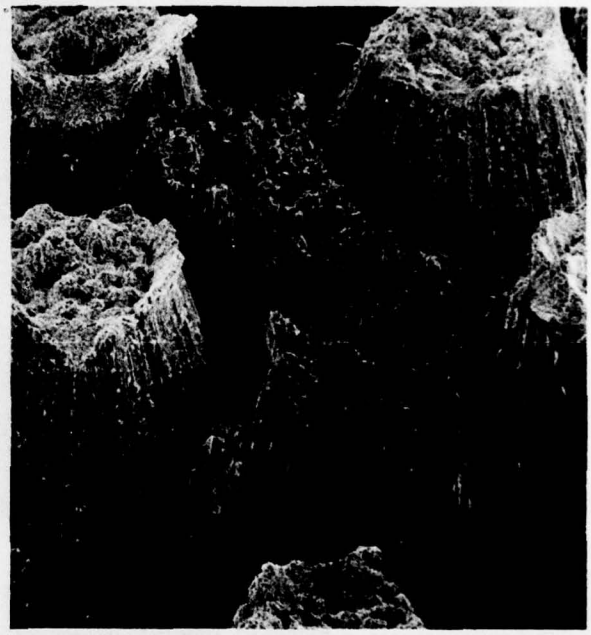


Figure 11. Stress - Rupture Data of W-2Th0_2 Composites.

(a)
Room Temp. (x 46)



(b)
1535 F (x 80)

Figure 12. S.E.M. Fracture Surface of 0.28 V_f Composite V Notch Charpy Specimen Tested at Room and Elevated Temperature.

TABLE IV.
TENSILE PROPERTIES OF COMPOSITES WITH MODIFIED MAR M322 COMPOSITIONS

Matrix Alloy	Fil Vol Fraction	Temperature °C	°F	UTS MN/M^2	Ksi	0.2% YS MN/M^2	Ksi	%el
Mar M322 (C)	0.33	RT		345	(50)	—	—	0.2
	0.35	900	(1652)	590	(85)	—	—	4.9
Mar M322 (D)	0.43	980	(1800)	545	(79)	537	(78)	4.7
	0.44	1093	(2000)	520	(75)	488	(71)	3.2
	0.40	1150	(2100)	420	(61)	392	(57)	4.0
	0.44	1315	(2400)	103	(15)	96.5	(14)	pull out
Mar M322 (E)	0.40	980	(1800)	545	(79)	537	(78)	—
	0.38	1093	(2000)	434	(63)	419	(61)	6.3
	0.40	1150	(2100)	448	(65)	392	(57)	5.0

TABLE V
STRESS-TO-RUPTURE DATA FOR COMPOSITES

Temperature °C	°F	Specimen Identification		V_f Ksi	Stress MN/m^2		Time Hrs.
1093	(2000)	(66)	Mar M322 (B)	0.42	206	(30)	50.5
		(67)	Mar M322 (B)	0.42	186	(27)	171.9
		(68)	Mar M322 (B)	0.42	206	(30)	111.9
		(70)	Mar M322 (E)	0.43	228	(33)	103.2
		(71)	Mar M322 (E)	0.45	172	(25)	239.4
		B(72)	Mar M322 (E)	—	48	(7)	89.3
		B(80)	Mar M322 (E)	—	34	(5)	212.4
		3 C T-9W	Mar M322 (B)	—	52	(7.5)	99
980	(1800)	(75)	Mar M322 (E)	0.35	207	(30)	518
		(76)	Mar M322 (E)	0.25	276	(40)	>60
1150	(2100)	(84)	Mar M322 (E)	0.42	138	(20)	25
		(85)	Mar M322 (E)	0.42	103	(15)	>1000

All runs were made in air except those at 2100°F.

(2000°F) for periods extending to 500 hrs. The rate of growth of the filament matrix interaction zone thickness was measured from the micrographs of the polished specimens. The data are summarized in Table VII.

Oxidation of the Matrix Alloy

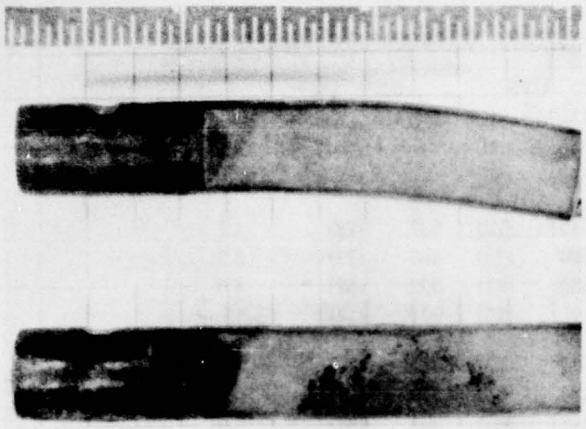
Preliminary runs were also made to study the cyclic oxidation behavior of Mar M322 alloy with varying W content. Specimens with 1cm diameter and 0.3cm thickness were exposed to air which was saturated with water vapor at 60°C, at a flow rate of 4cu ft/hr. At one hour intervals

TABLE VI
CHARPY IMPACT STRENGTH (IN-LB)

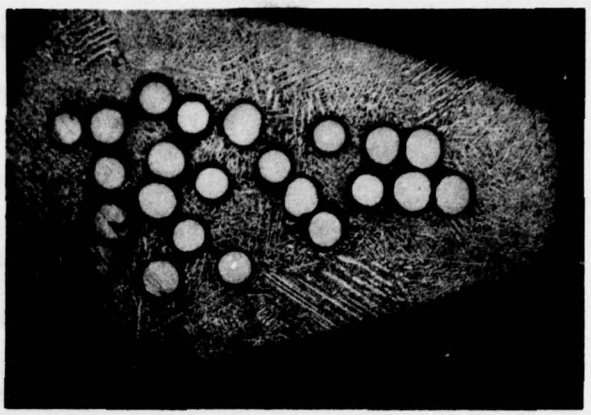
	RT	835°C
Matrix	17.2	21.8
Composite ($0.4V_f$)	20.6	280.0

TABLE VII
THICKNESS OF THE FIL-MATRIX INTERACTION ZONE AS A FUNCTION OF TIME
(MATRIX MAR M322 (E).

	AS CAST 8.0 MICRON (0.0003 in.)					
	980°C Micron	(1800°F) In.	1093°C Micron	(2000° F) In.	1150°C Micron	(2100°F) In.
25 hr.	—	—	—	—	15	0.0006
100 hr.	—	—	14	0.00056	—	—
250 hr.	—	—	24	0.00078	—	—
500 hr.	24	0.00075	31	0.00125	—	—
1000 hr.	—	—	—	—	38	0.00135



(a) Overall View of the Warped Specimen



(b) Transverse Section of the Thermally Fatigued Specimen Showing Fil-Matrix Debonding and Increased Diameter of Some Filaments.

Figure 13. Thermal Fatigue Bars Cycled Five Hundred Times at 450 ⇆ 1093°C (2.5 min heating, 2 min cooling).

each specimen was removed from the furnace, cooled to room temperature, weighed, rotated and returned to the furnace which was maintained at 1093°C. The specimen was weighed every hour for the first five hours and then at the seventh and tenth hour, and every five hours thereafter. After a total of fifty hours, the specimen was examined metallographically. Figure 14 shows a plot of the weight gain with time of various alloys including Mar M302, for comparison. Optical examination of the specimen after exposure both in these tests and in stress rupture tests, showed outer discontinuous film of CoO on a relatively more tightly bound layer consisting probably of $CoCr_2O_4 + CoWO_4 + CoO$.

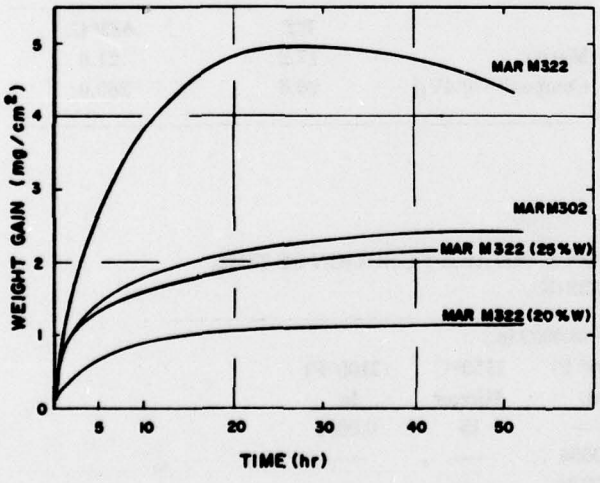


Figure 14. Cyclic Oxidation Rate of Matrix Alloys; Mar M302 and Mar M322 (E).

Evaluation of the Prototype Composite Blade

The prototype JT9D blade cast from the composite was sectioned and metallographically examined. Figure 15 shows that the infiltration of the matrix in the filaments was good and there was minimum fil-matrix interaction. However, there appeared to be a separation of the filament bundle from the matrix, in the concave areas of the blade. Some of these cracks (Figure 16) originated from the cracks in the filament which were present to start with. However, the major separation appeared to be due to mismatch in the coefficient of thermal expansion of tungsten and the cobalt alloy.

4. DISCUSSION

This study has clearly demonstrated the feasibility of fabricating W-2%ThO_2 filament reinforced cobalt alloy composite material, by the conventional investment casting process, not only in the form of the tensile, thermal fatigue and charpy specimens, but also prototype of first stage blades of JT9D engine. The significance of these results lies in the fact that the 0.4 V_f W-2%ThO_2 filament reinforced cobalt alloy composite for which the data are reported here, has an 100 hr. 1093°C (2000°F) rupture stress of 206 MN/M^2 and compared with 36 - 69 MN/M^2

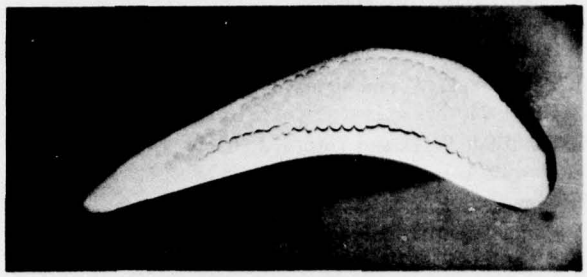


Figure 15. Transverse Section of the Blade Showing Crack.

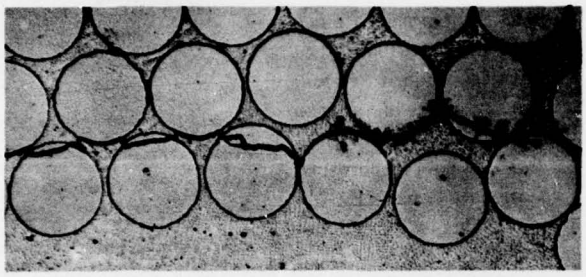


Figure 16. Showing Connecting Pattern of the Cracks Initially Present in the Filament.

(5 - 10 Ksi) for the best conventional superalloys, which means that the use of this composite could eliminate the necessity of providing the air cooling (or reduce its quantity) of the blades, resulting in fuel economy. Or if cooled, the rotor speed can be increased to achieve higher engine efficiency. Even on the basis of density normalized stress-to-rupture properties, this composite is superior to the current alloys, by a factor of two.

The use of conventional investment casting process to fabricate these blades will alleviate the need of additional capital investment, whereby the composite blades in addition to being superior in performance, could also be expected to be cost competitive. This may be particularly true for helicopter engine blades, which because of their small size may not be amenable to the fabrication process such as diffusion bonding.

The tensile data of the composite summaried in Table IV, show that average efficiency of the filament reinforcement of the matrix is between 70 - 85%. This may be due to the formation of a finite filament-matrix interaction zone, which is brittle and may have fine microcracks. At room temperature the composite always has very low strength, because of the brittleness of the filament.

Petrasek[4] has reported degradation of tungsten filament incorporated in nickel base alloys because of the recrystallization of the filament induced by the diffusion of nickel. In the present study, there was no evidence of such recrystallization as a result of casting or thermal exposures during stress rupture tests in the temperature range of 1800 - 2100°F for periods extending to 1000 hrs. The major cause of the degradation in these composites appears to be the formation of microcracks in the fil-matrix interaction zones. As seen from Table VII the thickness of this zone even after 500 hrs at 1093°C (2000°F) is not more than 31 microns (0.00125 in) as compared with 100 hr zone thickness of 50 - 100 microns reported in reference 4.

Although only a few tests were made, they clearly show that the filaments in the composite provide energy absorbing mechanism in the form of large fil-matrix interface, whereby the composite has much higher impact strength than the conventional superalloys, especially at elevated temperatures.

Thermal fatigue is an important problem which must be reckoned with, in the design of components in the high temperature section of the engine. The test made here was only for a low V_f composite, in which the filaments were nonuniformly distributed. In this test, understandably the coefficient of thermal expansion in the low V_f portion of the composite in the thinner portion of the specimen was higher than the thicker portion which had relatively more filaments. Therefore, during the thermal cycling the thinner edge experienced much larger strains at the filament matrix interface, warping the specimen. The alternating stresses during the thermal cycling at the interface also resulted in the debonding of the filament from the matrix, and in some cases deformation of the filaments themselves. Tests by Signorelli[8] et al on W filament — FeCrA1Y matrix showed that while the low V_f composite showed similar behavior, that is, warping, the composites with higher V_f (0.4 - 0.5) did not have this problem. Therefore, before any conclusion can be drawn, it is necessary to test W-2%ThO_2 - Mar M(E) composites with high V_f (0.4) under similar conditions.

It is recognized that in order to use this composite at 1093°C (2000°F), it is necessary to apply a protective coating to reduce the oxidation and hot corrosion. Preliminary oxidation runs made here show that increasing the tungsten content of the matrix from 9 to 25% did not significantly enhance the rate of oxidation, as was suspected. In actual fact, it was lower than the standard alloy. This observation is supported by a recent study reported by Dashan[9] et al, in which it is shown that in W-Cr binary alloys, increase of tungsten decreased the oxidation rate. The decrease is more pronounced in alloys containing 15 Cr, than those containing 25 Cr. Formation of $CoWO_4$ phase in addition to $CoCr_2O_4$ in the inner CoO scale, which reduces the cross-sectional area through which outward diffusion of the cations could take place, is suggested as a possible mechanism of this effect.

The fabrication of JT9D blade from this composite without any extraordinary difficulty is very encouraging.

However, it is only a preliminary effort. Much more work must be done to optimize the solidification parameters of the composites so that crack free blade castings are achieved. Also the filaments at the tip of the blade have either to be ground and/or protected with a coating to be applied by one of the conventional processes, or the design of the wax patterns will have to be modified in such a way that the filaments remain within the body of the matrix. In any case, in order for this blade to perform at 2000°F, it has to be protected with some thermomechanically compatible coating such as CoCrA1Y or FeCrA1Y. It may further be conjectured that if required, cooling channels can also be provided in this blade, to prolong its service life.

5. CONCLUSIONS

A cobalt base alloy reinforced with 0.42 V_f W-2%ThO_2 filament, fabricable by the conventional investment casting process, with a 100 hr 1093°C (2000°F) stress-to-rupture of 206 MN/M^2 (30 Ksi) has been developed. This represents an advantage of 200°F in temperature and a superiority of specific stress-to-rupture by a factor of 2 over the conventional alloys. Also it has, for the first time been demonstrated, that a real life JT9D blade can be made from this composite, using the state-of-the-art technology and equipment.

More work is necessary to optimize the process further to achieve crack free castings of the blades and if possible with the tungsten filament bundle remaining within the matrix envelope at the tip end of the blade. Also, more data are necessary on the thermal fatigue and creep behavior of this composite, with and without protective coatings. Another possible area of development could be the modification of matrix composition to achieve higher room and elevated temperature ductility and superior oxidation and corrosion resistance. Low and high cycle fatigue behavior of this composite must also be investigated. Work in this area is in progress.

In the homogeneous alloys, the formation of TCP phases such as sigma phase is considered to be very detrimental, because this phase can provide mechanisms of crack initiation in the alloy. A Phacomp analysis has shown that Mar M322 (E), has a n $\bar{V}$ number of 2.6 which is within the safe limits. However, the significance of sigma phase in the presence of reinforcing continuous filaments, is a question which as yet remains unanswered.

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The assistance of R. Warenchak and R. Wharton in the measurement of the mechanical properties of the composite specimens and of G. E., Schenectady and TRW, Cleveland in investment casting of specimens and turbine blades is gratefully acknowledged. This work was performed under an AMMRC funded program.

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