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METAL MATRIX COMPOSITES FOR AIRCRAFT PROPULSION SYSTEMS

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INTRODUCTION

Studies of advanced aircraft propulsion systems have indicated that performance gains and operating costs are possible through the application of metal matrix composites. Compressor fan blades and turbine blades have been identified as components with high payoff potential as a result of these studies. This paper will present the current status of development of five candidate materials for such applications. Boron fiber/aluminum, boron fiber/titanium, and silicon carbide fiber/titanium composites are considered for lightweight compressor fan blades. Directionally solidified eutectic superalloy and tungsten wire/superalloy composites are considered for application to turbine blades for use temperatures to 1100 C (2000 F).

POTENTIAL COMPOSITE BLADE BENEFITS AND PROBLEMS

As with most new materials, composites are in competition with standard or conventional materials for component applications. Designers usually design a component using proven current materials and substitute the new material only after studies have been undertaken to develop experience and confidence. While composite hardware programs have been largely substitutional, engine system studies have been performed to indicate the potential advantages of composites when incorporated in the design stage. Fan and turbine blades have been identified in these studies as components with high payoff potential. The studies, summarized in ref. 1, have indicated advantages as shown in figure 1. This figure shows the benefits accrued by an advanced engine configured to use the higher strength and stiffness potential of composite fan blades and the higher creep-rupture strength and higher use temperature potential of superalloy-matrix composite turbine blades. Comparison is made with an equivalent engine using current materials. The redesigned engine involves fewer fan and compressor stages, a reduced number of turbine stages, a reduced number of bearings and a shortened overall length. A smaller and lighter engine is therefore possible through the use of composites.

However, there are some technical problems to overcome before composite component reliability is established and such an engine can be built. The metal matrix composite candidates for application to fan and turbine blades as discussed in this paper are shown in table I. The table also shows the major problem areas under study to ready these materials for engine component application.

Fan Blades

B/Al Impact Resistance

More research and development effort has been devoted to boron/aluminum (B/Al) for fan blade application than any other metal matrix composite. This composite has been developed to a state of readiness very near that required for successful full scale engine operation of a fan blade set in ground engine tests. The ground engine test, which would include evaluation of resistance to foreign object damage, would serve to prepare the material for flight demonstration.

The performance and properties demonstrated by B/Al in studies conducted thus far have been adequate for fan blade application with one exception. Resistance to large object impact, such as birds, has varied greatly. Resistance to erosion from sand and rain has been adequate, as has been impact resistance to gravel and ice balls. Large object impact (such as birds) usually caused fracture of large portions of the airfoil. Poor impact performance is not unexpected based on comparison of pendulum impact strength values shown in figure 2 for titanium (ref. 2) and typical values for B/Al composites used in the initial studies (ref. 3). Since the composite impact values were less than half of the value for titanium, B/Al blade failure from impact is not surprising. Improved impact resistance is therefore required to apply B/Al to blades in the forward section of turbofan engines.

Studies to understand and improve impact resistance have been conducted at several laboratories (refs. 3-8). The results discussed below are from programs conducted at the Lewis Research Center and at TRW under NASA funding. The variables included in the programs are shown in table II. The choice of variables was influenced by efforts to minimize the embrittling effect of the low strain-to-failure boron fiber on the otherwise relatively ductile, tough aluminum alloy. Matrix alloys were chosen to further increase ductility and failure strain. Large diameter fibers were selected to increase the interfiber distance in the composite, thereby reducing the volume of matrix constrained by the elastic fibers. Fabrication processing was varied to obtain densification of the composite and a high degree of bonding between ply layers. However, bonding temperatures were maintained as low as possible to minimize reaction at the fiber-matrix interface since reaction has been shown to reduce the mechanical properties of B/Al.

A significant improvement in impact resistance of B/Al was obtained using these approaches. Some of the improvements are illustrated in figure 3. Matrix alloys 5052 and 1100 were selected because they have lower yield strengths and larger tensile strain-to-failure values. Increasing the ductility of the matrix by selecting a different alloy increased the impact strength of the composite. Notched Charpy values increased from 18 joules (13 ft-lbs) with 5052 Al alloy matrix to 64 joules (48 ft-lbs) with 1100 Al matrix. Increasing fiber diameter resulted in a further significant improvement in impact to 96 joules (71 ft-lbs).

The impact resistance was also strongly influenced by processing conditions. The bonding temperature which contributed to high impact strength varied with the matrix alloy used as well as the fabrication process. It does appear that the lowest bonding temperature, at which good bonding can be achieved, is generally the most desirable. Previous work (ref. 9) has shown that fatigue resistance can be degraded by increasing bonding temperature from 450 to 475 C. The fatigue strength reduction was related to an increase in the reaction

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zone at the B/Al interface. An increase in the reaction zone might also be expected to reduce fiber strain to failure and thereby the energy absorption capability. Decreased impact strength can also result from too low bonding temperature. Too low a temperature can result in inadequate bonding. Delamination between monotape plies or at the fiber/matrix interface can then occur prematurely at relatively low applied stress levels. Bonding temperatures between 455 and 482 C (850 - 900 F) appear to give high impact values.

The marked impact improvement in impact resistance of B/Al is illustrated in figure 4 by comparison with a typical titanium fan blade material and previous B/Al composite impact values. A ten-fold increase in laboratory pendulum impact values is very encouraging but not necessarily indicative of satisfactory foreign object damage resistance at the high velocity of fan blade operating conditions. However, high velocity ballistic impact tests on static test specimens of improved B/Al have indicated similar trends of increased impact resistance (ref. 8).

Improved impact resistant B/Al is now being applied to fan and compressor blades and preliminary results are encouraging. The recent successes with B/Al composites suggest that FOD resistance, the remaining major technical impediment to successful B/Al fan blade flight demonstration may be overcome.

B/Al Fan Blade Cost Considerations

One of the more difficult tasks involved in applying composite materials is to estimate realistic cost benefits. The labor-intensive research and development fabrication techniques commonly used for composites, combined with limited production experience, form a questionable basis for cost projections. However, B/Al has been studied for about ten years and a number of detailed cost projections have been made (ref. 1). The cost projections shown in table III are based upon boron filament and tape costs that have been projected by representatives of the producers and require no new technology. The $250/kg price is fairly close to the current large order price. At that B/Al cost, the fan blade cost is equivalent to that for conventional forged titanium blades. The cost benefits that may be achieved by lower cost components are often the primary justification or mandatory prerequisite to applications of new technology in the harsh economic climate that prevails today. As shown in table III, it is anticipated that reductions in the cost of B/Al will permit blade costs substantially lower than that of forged titanium.

B/Ti and SiC/Ti

Titanium matrix composites also have been developed for application to fan blades. Filament reinforcement of the standard fan blade material would seem to be a logical candidate for intensive development as a fan blade. However the severe fiber degradation encountered during the high temperature exposure required for fabrication has discouraged early research efforts (refs. 10-11). Although the level of titanium matrix composite research has been limited, some progress has been made as indicated by the properties listed in table IV (ref. 1). The high shear strength and transverse properties, combined with the relatively good retention of strength to 538 C (1000 F), make the material a good candidate for elevated temperature blade application in turbojet engines. The erosion resistance of titanium to ice, sand, and rain for fan blade applications has been well established by years of service. Another important advantage of titanium matrix composites for elevated temperature applications is the thermal expansion match of matrix and fiber. Thermal fatigue failure can be the limiting failure mode for the type of cyclic operation that is typical for fan blades. The "typical" operating cycle for aircraft engines in commercial service in the U. S. is estimated to be one hour with about 3000 hours of operation each year. The 3000 heating and cooling cycles per year can cause failure of turbine blades and could conceivably cause problems in the case of high temperature fan and compressor blades.

The high shear and transverse properties of titanium matrix composites may also make angleply orientation unnecessary thereby simplifying fabrication and reducing cost.

However, this class of materials is not without problems. In addition to the fiber degradation caused by high fabrication temperatures, the density of titanium composites is higher than that of B/Al. The specific modulus values of both types of composites are about equivalent, but the specific tensile strength values are lower than those of B/Al. Very limited impact data have been published; however the notched Charpy impact values reported (ref. 12) were 7 joules (5.2 ft-lbs) or lower. Notched unreinforced titanium

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impact values are about 20 joules (15 ft-lbs). Titanium matrix composites may benefit from an impact improvement study similar to that conducted with B/Al. Since unnotched titanium specimens have demonstrated pendulum impact strengths over 135 joules (100 ft-lbs), as indicated in ref. 8, it might also be expected that titanium composites would have the potential for higher impact strengths than those obtained thus far.

Titanium composite fan blades have been fabricated with both boron and SiC fibers and cost analysis projections for large scale production (ref. 13) indicate that they can be cost competitive with titanium alloy blades.

Turbine Blades

Directionally Solidified Eutectics

Gas turbine engine cycle studies have indicated that significant benefits in cost, size, weight, and performance are possible through the use of advanced composite technology. Higher cycle temperatures are beneficial and superalloy turbine blades typically are cooled to permit higher turbine inlet temperatures than would be possible otherwise. Cycle studies also indicate that higher combustion temperatures are countered by the need to decrease exhaust pollutants such as nitrous oxide and the need to reduce engine noise generation. Both noise and pollution emissions are generally more severe with higher temperatures. One of the ways that composite turbine blade materials can be used more efficiently is to decrease the amount of cooling now required in the higher temperature forward turbine stages. In addition, the rear stage blades, which are now cooled a small amount, might be operated without cooling entirely. The higher temperature capability of composites could make such an overall reduction in cooling air possible. Another way to increase performance and decrease engine weight would be by increasing the rotational speed of the engine. The higher strength of the composite blades could permit such an increase, which in turn could decrease engine size and weight as indicated in figure 1. The increased payoff obtained in line with the above discussion would not increase noise or pollution since neither the combustion temperature nor the jet exhaust velocity would be increased.

Directionally solidified (d. s.) eutectics (in-situ composites) are being developed for the first generation composite turbine blades. Two eutectic systems have been selected for development (refs. 14-17). Micrographs of rod and lamellae reinforcement are shown in figure 5. The reinforcement in both of these composites is formed in-situ when the alloys are directionally solidified under stringent conditions to achieve planar front solidification with the reinforcement aligned in the growth direction.

Rupture properties of three d. s. eutectic alloys are shown in figure 6, along with data for one of the strongest conventional superalloys, TRW-NASA VIA alloy. All of the eutectics are superior to the superalloy at both 980 C (1800 F) and 1090 C (2000 F). There are minor differences between the two nickel-base dispersion strengthened eutectics shown, which are currently considered leading candidates for turbine blade applications (ref. 17).

While d. s. eutectics are stable for long times at high temperatures, thermal cycling or thermal gradients, both of which are encountered under normal service conditions in gas turbine engine operation, can cause structural instability. This has caused degradation of composite properties for some compositions. However, at least some compositions of TaC and Ni_3Nb reinforced eutectics have demonstrated resistance to thermal cycling (ref. 18).

Studies are underway to increase shear strength and transverse ductility. Oxidation protection for exposed surfaces is also required, as is the case for conventional superalloys used in turbine blade applications.

Coatings do not remain defect free for the long lives (typically 3000 - 8000 hours) expected for turbine blades and it is important to provide a margin of oxidation resistance in the uncoated composite. Therefore, the relative ability to provide adequate oxidation protection may be one of the deciding factors in determining which composition will eventually be chosen for blade use.

Blade cost is also a factor in developing d. s. eutectics for blade application. While production of complex blade shapes has been demonstrated (refs. 15-16), growth rates are generally 2 - 10 cm/hr and careful quality control and inspection are need to assure safe blades. The ductility of d. s. eutectics is generally lower than that of the superalloys they are intended to replace. However, the acceptance of reduced ductility by gas turbine engine designers is a continuing trend. Cast superalloys were regarded with skepticism because of lower ductility and variable properties when forged superalloys were the standard blade material. The sizable effort currently being conducted to use SiC and other brittle ceramics in turbines is a good indication of this trend. While there are still some problems to overcome, researchers working in the field of d. s. eutectics are confident that turbine blades of these materials will be operated in gas turbine engines in the foreseeable future.

Refractory Wire Superalloys

Refractory wire/superalloy composites also have been the subject of study for application to turbine blades. They have been investigated at a number of laboratories (refs. 19 - 24). This type of composite has the potential for application at temperatures above those of the d. s. eutectics currently being developed, as shown in figure 7. The development and application of refractory wire/superalloy composites could permit use temperatures as high as 1150 C (2100 F) without diffusion barrier coated fibers and as high as 1200 C (2300 F) with diffusion barriers. Rupture strength and impact resistance have been demonstrated with laboratory data (refs. 22 and 24).

Density-normalized rupture data at 1090 C (2000 F) are shown in figure 8. The strengths of the refractory wire/superalloy composites are up to four times greater than those of conventional superalloys and twice those for the d. s. eutectics. Further strength increases of refractory wire/superalloys are possible to increase this advantage. The potential strength for diffusion barrier coated wire has been calculated to be as high as from four to six times the density-normalized values for d. s. eutectics at 1090 C (2000 F).

Refractory wire/superalloys have been fabricated that have Charpy and miniature Izod impact strengths that compare favorably with those obtained with superalloys at normal blade temperatures. However, few data have been obtained to indicate resistance to oxidation, erosion, and thermal and mechanical fatigue. Furthermore, the specimens evaluated in most programs have been fabricated using powder metallurgy methods which are not ideally suited to low cost blade production. Diffusion bonding of monolayer tapes of refractory wire/superalloy would be preferred for volume production and also adds to the potential for improved properties. Improved ductility can be incorporated by using wrought superalloy foils instead of hot pressed powders. Also, fully densified superalloy foil may reduce fiber/matrix reaction.

Monolayer tape fabrication of refractory wire/superalloy composites has been developed using the process shown schematically in figure 9, taken from ref. 25. Both powder cloth and alloy foil have been used successfully. The high cost of obtaining small quantities of foil of a number of research alloy compositions was avoided by using powder cloth. However, it is envisioned that alloy foil will be more efficient for volume production. Press bonding has been used for much of the research effort, becuase of the ease of producing small research quantities with varying compositions. However, for large volume production, the effort to develop the proper conditions of pressure, roll speed, and temperature can be justified to achieve rapid, high volume, low cost production of monolayer tape. The processing of turbine blades fabricated using this method should be similar in labor and processing and therefore the costs should approach the fan blade costs described earlier in the paper.

The micrograph in figure 10 shows the excellent quality of densification and the lack of fiber/matrix reaction obtained with press bonded monotape. Similar quality monotape was achieved with a limited amount of roll bonded tape. Even more significant was the limited depth of reaction which occurred at the fiber/matrix interface with test specimens fabricated by secondary diffusion bonding of monolayer tape. The micrographs in figure 11 show the limited depth of reaction (0.001 cm) obtained after 200 hours at 1190 C (2000 F). This reaction depth is about that obtained with as-fabricated powder metallurgy specimens. Previous studies (refs. 21, 22, and 26) have shown that composite properties correlate with reaction depth. Since increased reaction depth results in reduced properties, the limited reaction should result in retention of high rupture strengths.

The data currently most needed are concerned with the performance of refractory wire/superalloy composites in cyclic thermal fatigue tests. Very few tests have been conducted in the past and results have been mixed. The concern stems from the large thermal mismatch of nickel superalloys and tungsten wire. Thus, the thermal fatigue resistance of refractory wire/superalloy composites must be demonstrated for them to be considered candidates for use as turbine blades in aircraft turbine engines. Land based turbines and other applications that do not have short operating cycles would require less resistance to thermal fatigue.

Although limited in amount, the thermal fatigue data obtained recently for refractory wire/superalloy composites are very encouraging. The photos in figure 12 show a specimen tested for 1000 cycles from 85 to 2200 F in a Naval Air Systems Command program conducted at TRW. The specimens were direct-resistance-heated in a Gilmore Universal testing machine. No matrix or fiber cracking was apparent in the W-1 ThO_2/FeCrAlY composite. These preliminary results suggest that thermal fatigue failure of refractory wire/superalloy composites may not be a serious problem.

CONCLUDING REMARKS

Significant progress has been made in the development of composites for application to aircraft propulsion systems. The progress is particularly noteworthy because it has been achieved in an enviroment of cost competitiveness in which acceptance of new technology is difficult.

Boron/aluminum has demonstrated a marked improvement in impact resistance. These results give hope that FOD resistance, the remaining technical impediment to flight demonstration of B/Al blades can be overcome. Efficient, automated blade fabrication procedures have been identified which have the potential to produce fan blades at equivalent or lower cost than forged titanium blades.

Titanium-matrix composites with boron or silicon carbide reinforcement have demonstrated good properties at room and elevated temperatures. These properties indicate that titanium-matrix composites also should be candidates for fan blade applications for elevated temperatures.

Directionally solidified eutectics are being considered for turbine blade applications at blade material temperatures at least 50 C (100 F) above those currently used for conventional superalloys. Compositions have been identified and mechanical property data have been obtained to indicate a good potential with d. s. eutectics for achieving turbine blade use temperature increases within these goals.

Tungsten wire reinforced superalloy composites are being developed for application at blade use temperatures of at least 100 C (200 F) above those of the first generation of directionally solidified eutectics. Fabrication processing of refractory wire/superalloy composites from secondary diffusion bonding of monolayer tape has been developed. Test specimens made from monolayer tape have shown reduced fiber/matrix reaction and improved stress-rupture properties compared to previous composites made by a powder metallurgy method. Preliminary thermal fatigue results indicate that this failure mode may not be a serious problem.

The outlook is bright for application of metal matrix composites to aircraft propulsion systems, as well as to other aerospace systems.

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TABLE I. - PROBLEM AREAS FOR COMPOSITE ENGINE COMPONENTS

COMPONENT	METAL MATRIX COMPOSITE	MAJOR PROBLEM AREAS
FAN BLADES	BORON/ALUMINUM	IMPACT RESISTANCE BLADE COST
	BORON/TITANIUM	PROPERTY CHARACTERIZATION
	SILICON CARBIDE/TITANIUM	IMPACT RESISTANCE
TURBINE BLADES	DIRECTIONALLY SOIDIFIED EUTECTICS	PROPERTY OPTIMIZATION SERVICE SIMULATION TESTS COSTS
	REFRACTORY WIRE/SUPERALLOY	FABRICATION PROCESSING THERMAL FATIGUE TESTS

TABLE II. - VARIABLES FOR B/Al
IMPACT IMPROVEMENT STUDY

FIBER DIAMETER
MATRIX ALLOY DUCTILITY
FABRICATION PROCESSING
FIBER PLY ORIENTATION

TABLE III. - FAN BLADE COST

TITANIUM		BORON/ALUMINUM	
$150/BLADE		$150/BLADE	B/Al TAPE AT $250/KG ($115/LB)
		$100/BLADE	B/Al TAPE AT $55/KG ($25/LB)
	COSTS BASED ON:	FIRST STAGE BLADE	25 CM LENGTH
		6.25 CM CHORD	10 000 BLADES PER YEAR FOR 5 YEARS

TABLE IV. - TYPICAL PROPERTIES OF BORON/TITANIUM AND SILICON CARBIDE/TITANIUM (Ref. 1).

Material system	Test temperature, °C	Tensile strength				Elastic modulus				Shear strength	
		Longitudinal		Transverse		Longitudinal		Transverse			
		MN/m²	ksi	MN/m²	ksi	GN/m²	msi	GN/m²	msi	MN/m²	ksi
B/Ti 50 v/o 100 μmB	Rm.	1241	180	455	66	241	35	179	26	---	---
SiC coated B/Ti 50 v/o 100 μmB	Rm.	1310	190	517	75	248	36	200	29	496	72
	538 (1000° F)	827	120	345	50	207	30	165	24	---	---
SiC/Ti 50 v/o 100 μm SiC	Rm.	1207	175	517	75	262	38	207	30	448	65
	538	1034	150	345	50	221	32	172	25	262	38

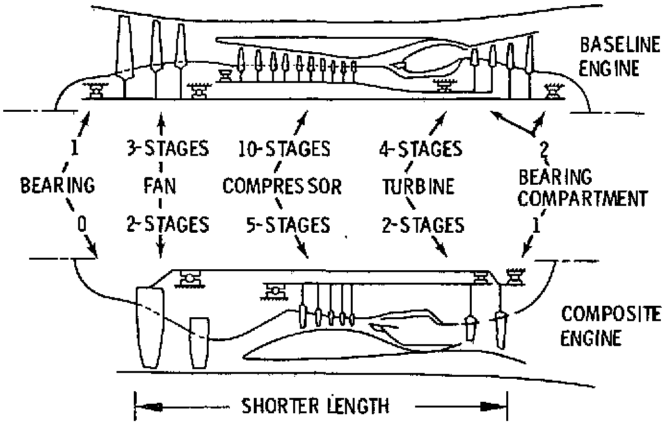

Figure 1. - Benefits from composite turbine blades.

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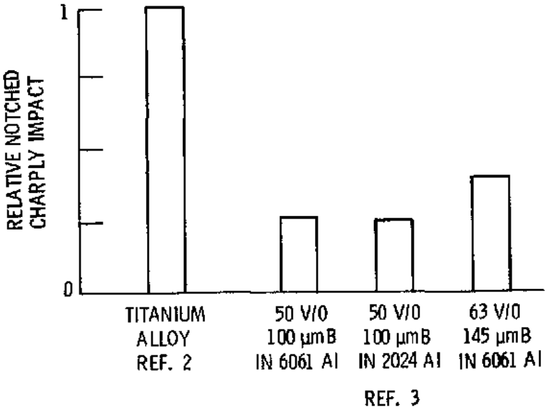
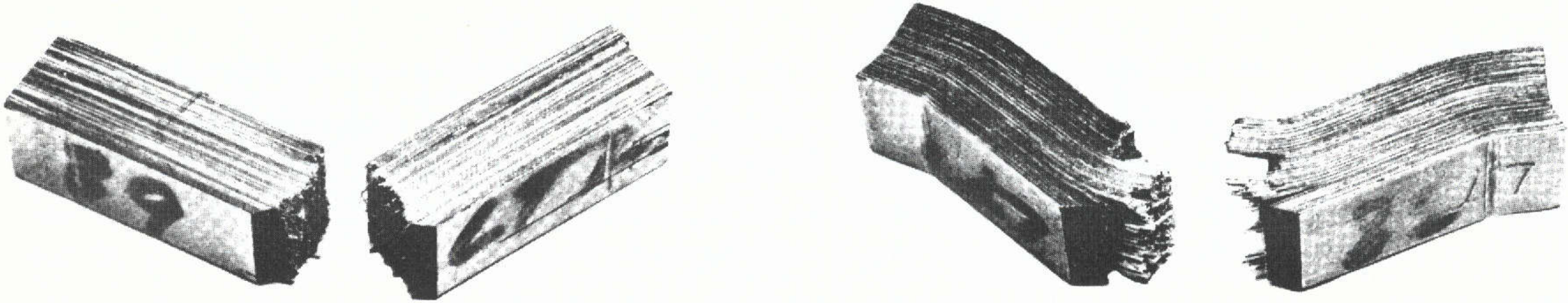


Figure 2. - Impact strength of titanium alloy and early B/Al composites.



18 JOULES (13 FT-LB)
50 V/O 0.14 MM B IN 5052 Al
(UNIDIRECTIONAL)

64 JOULES (47 FT-LB)
50 V/O 0.14 MM B IN 1100 Al
(UNIDIRECTIONAL)

96 JOULES (71 FT-LB)
50 V/O 0.2 MM B IN 1100 Al
(UNIDIRECTIONAL)

Figure 3. - Improved B/Al impact resistance.

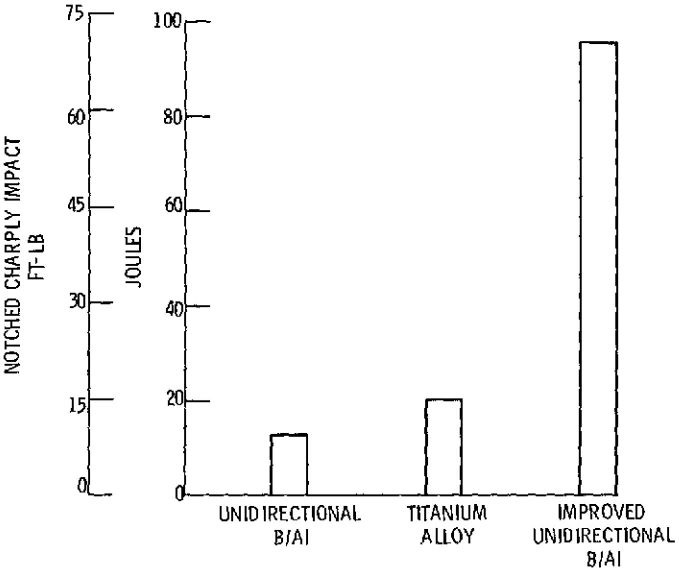
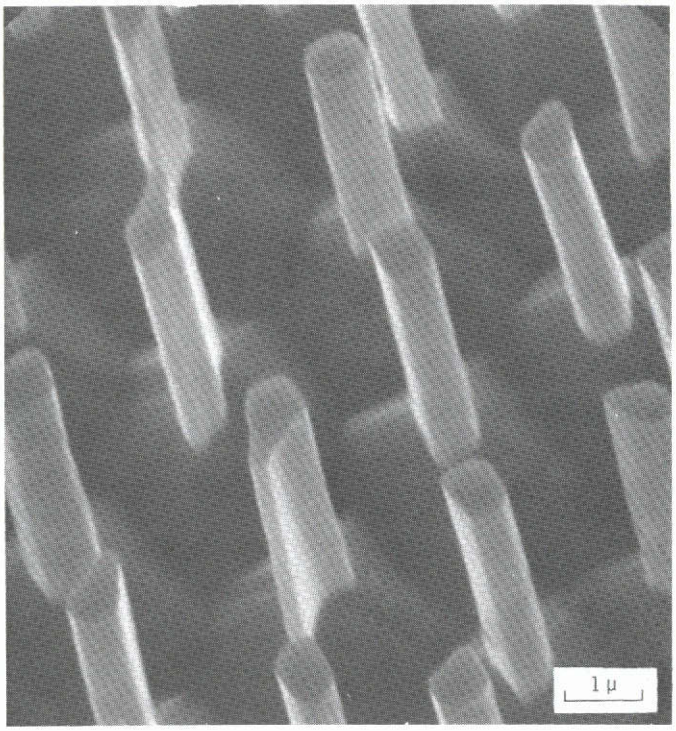
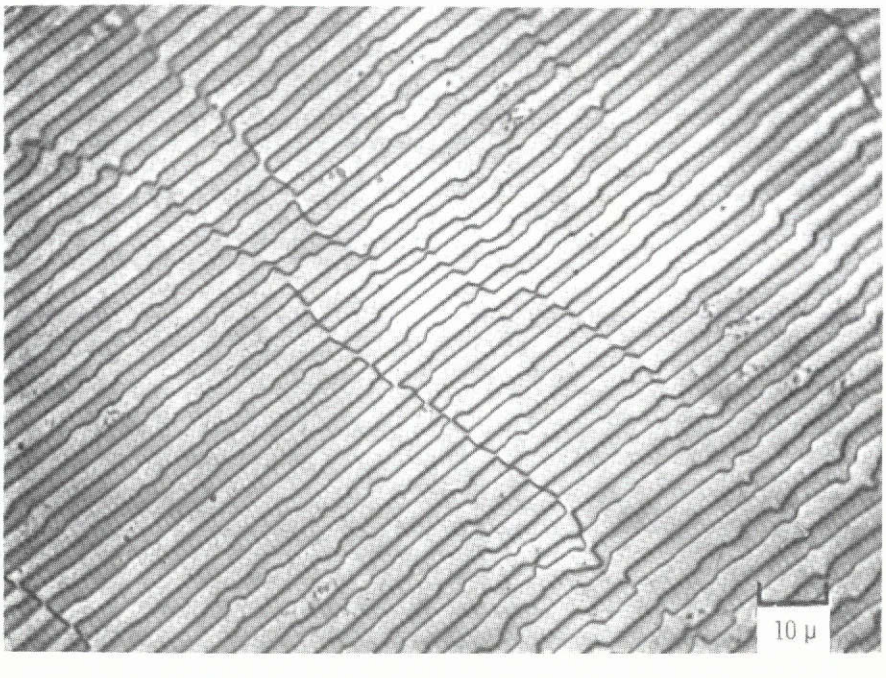


Figure 4. - Improved B/Al impact resistance.



ROD TaC IN COBALT BASE SUPERALLOY. (REF. 14).



LAMELLAR Ni3 Nb IN NICKEL BASE SUPERALLOY. (REF. 15).

Figure 5. - Potomicrographs of directionally solidified eutectics.

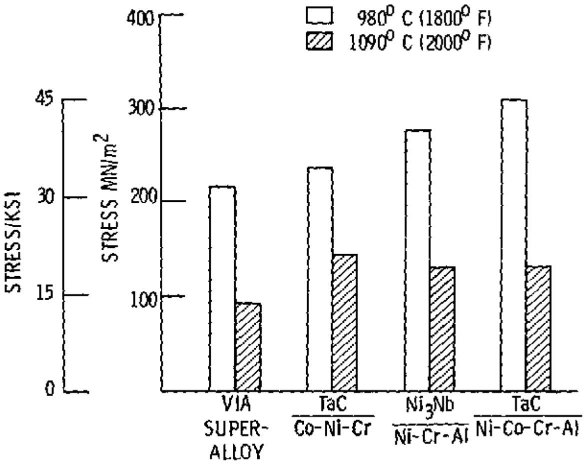


Figure 6. - 100 hour rupture strength of D.S. eutectics (ref. 15).

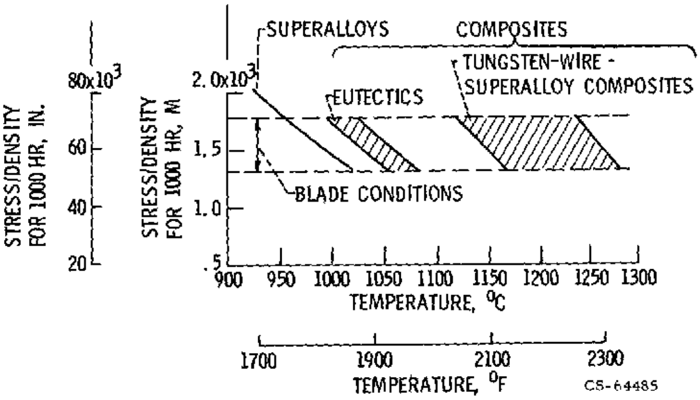


Figure 7. - Potential blade use temperatures for 1000-hour life.

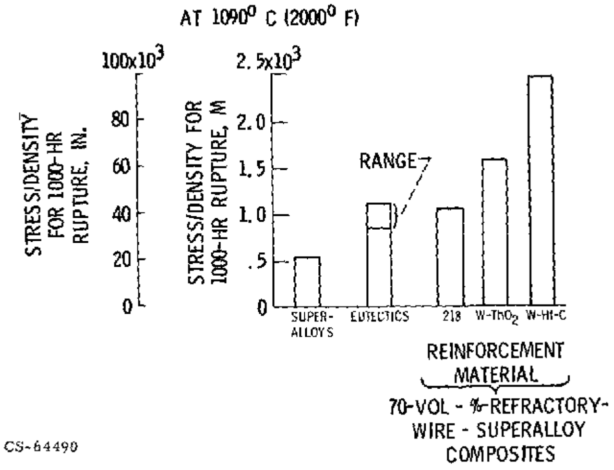


Figure 8. - 1000-hour stress rupture properties of refractory-wire - superalloy composites.

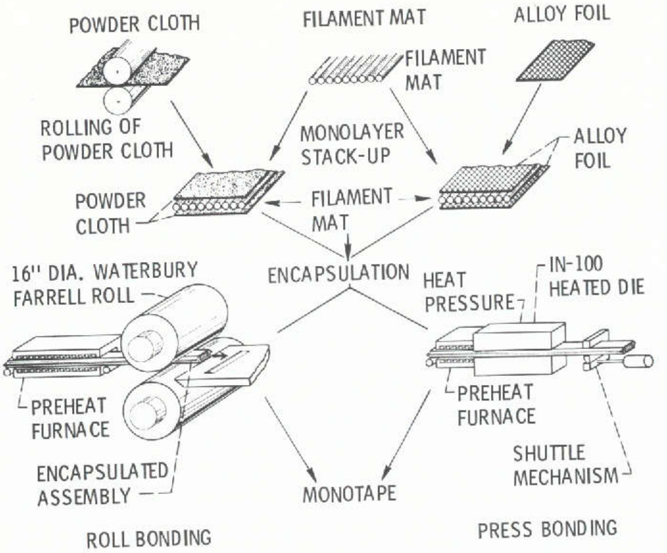


Figure 9. - Flow diagram of diffusion bonding techniques for the manufacture of W fiber-Ni alloy matrix monotapes.

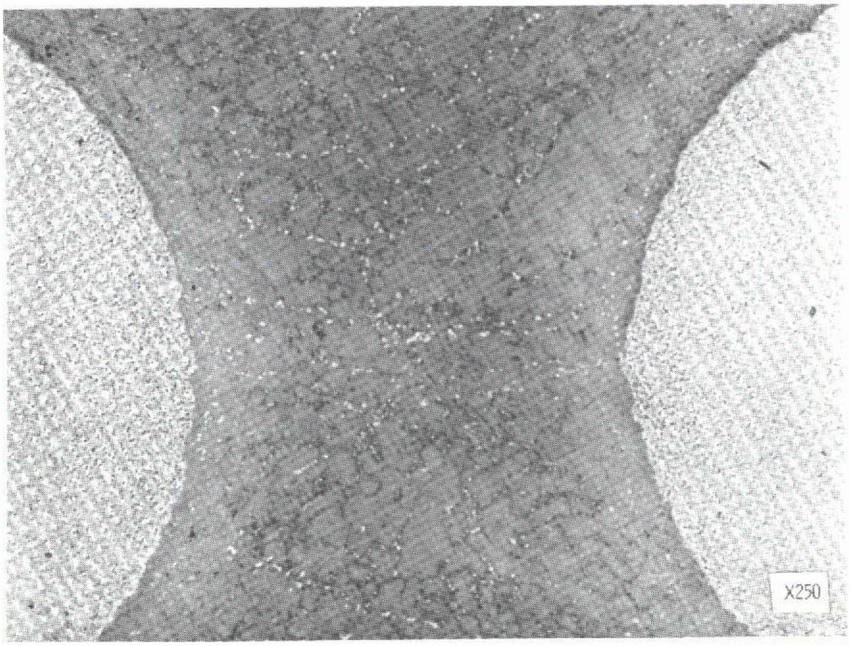


Figure 10. - Tungsten wire/superalloy monotape. (Ref. 25.).

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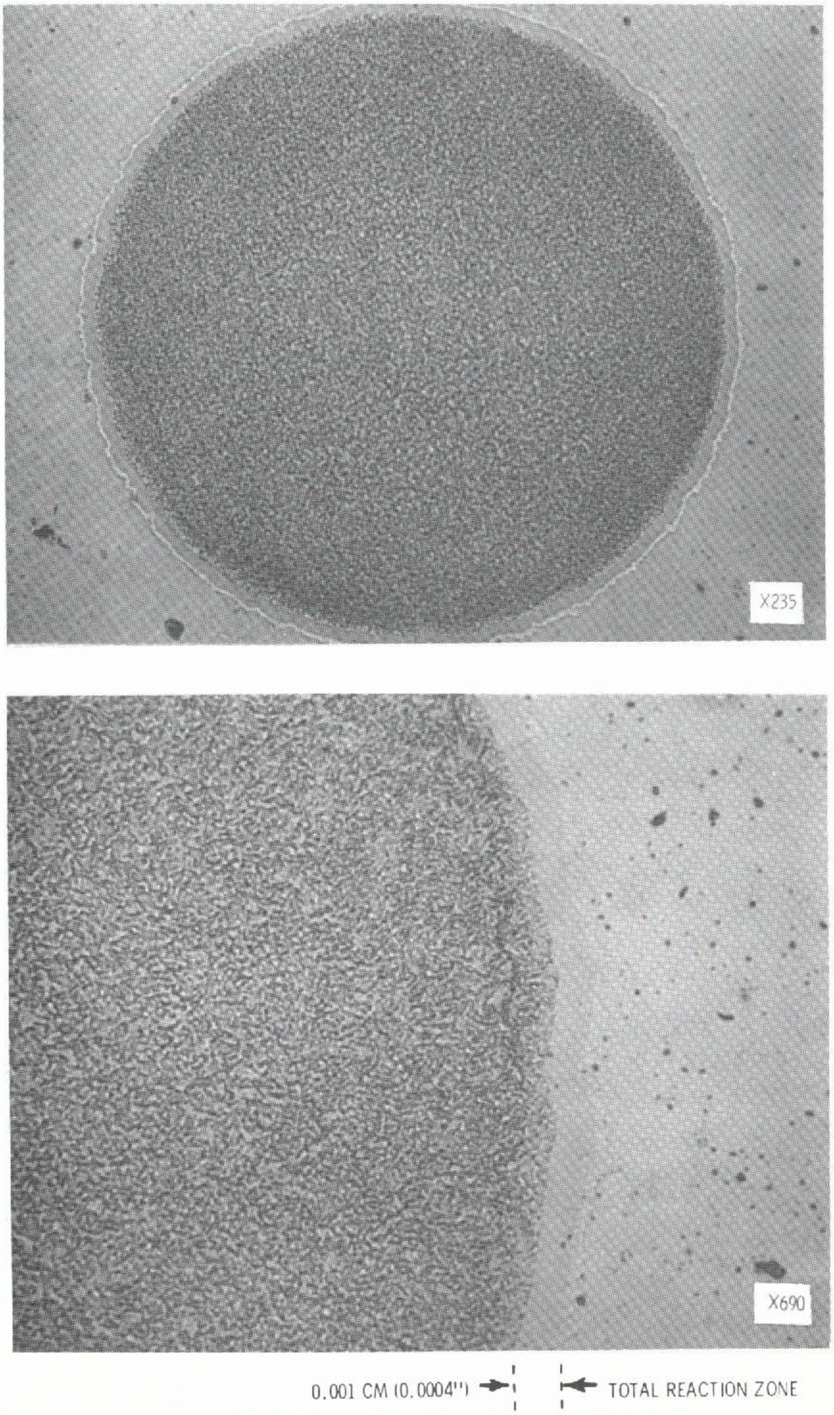
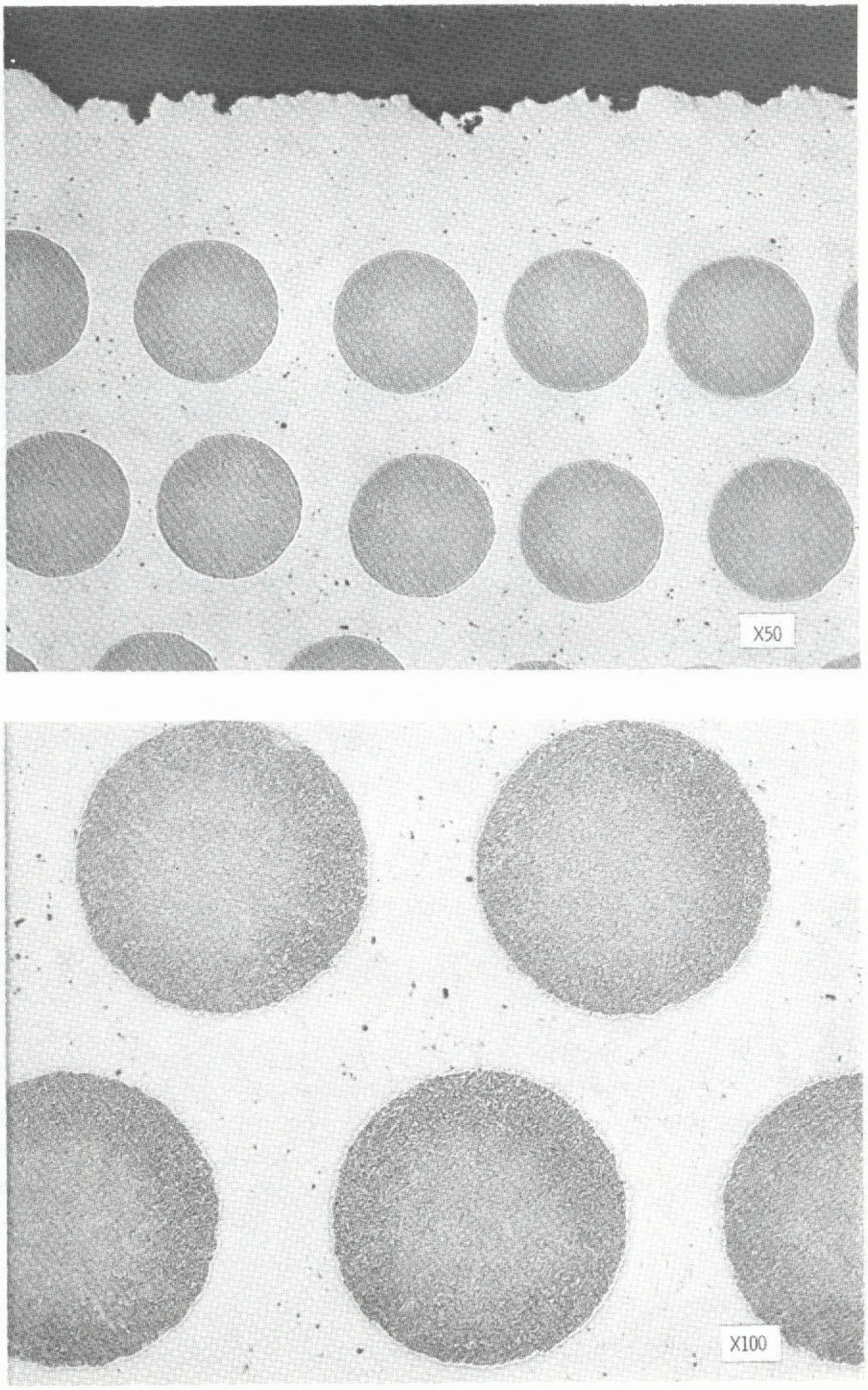


200 HOUR - 1090° C (2000° F) STRESS RUPTURE TEST. (REF. 25).

Figure 11. - Fiber-matrix reaction of tungsten wire/superalloy monotape.



1000 CYCLES 30 - 1200° C (85 - 2200° F).

Figure 12. - Photomicrographs of thermally cycled tungsten wire reinforced superalloy composite. (Photos courtesy of Irving Machlin).