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REVIEW OF STATUS AND POTENTIAL OF TUNGSTEN-WIRE — SUPERALLOY COMPOSITES FOR ADVANCED GAS TURBINE ENGINE BLADES

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16. Abstract

The current status of development of refractory-wire - superalloy composites and the potential for their application to turbine blades in land-based power generation and advanced-aircraft engines were reviewed. The data obtained thus far suggest that refractory-wire - superalloy composites have considerable potential for application as turbine blades at use temperatures to 1200° C (2200° F) and above. Additional laboratory and simulated service test data are needed, particularly for oxidation and thermal and mechanical fatigue resistance, to complete the evaluation of the materials.

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REVIEW OF STATUS AND POTENTIAL OF TUNGSTEN-WIRE - SUPERALLOY COMPOSITES FOR ADVANCED GAS TURBINE ENGINE BLADES

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SUMMARY

Fiber-reinforced composite materials have been intensively studied recently because they offer the potential for substantially improved properties compared to bulk metals and consequently have considerable promise for use in various engineering systems. For example, increased operating temperatures for turbojet engines may be possible with composites. This report reviews the current status of development of refractory-wire - superalloy composites with a particular view toward their potential for application to turbine blades in advanced aircraft and land-based turbine engines.

Refractory-wire - superalloy composites have demonstrated sufficiently high rupture strength and impact values to suggest that they have considerable potential for application to turbine blades at increased operating temperatures. Successful development and application of such composites to turbine blades could permit blade use temperatures as high as 1150° C (2100° F) without the use of diffusion-barrier-coated fibers and as high as 1260° C (2300° F) with diffusion barriers. Turbine blade material temperatures of 1150° to 1200° C (2100° to 2200° F) for a relatively simple convection-cooled composite blade might permit gas-turbine operation at turbine-inlet temperatures over 1650° C (3000° F).

Turbine blade weight for a solid blade of tungsten-wire - superalloy composite need not exceed that for conventional superalloys if reasonable measures are taken with the composite. Two variables can be used to overcome the high density of the refractory fiber: The fiber content can be varied along the blade span so as to tailor strength to that needed, and the blade thickness can be slightly reduced near the base as permitted by the improved strength-density ratio of the composite.

INTRODUCTION

Fiber-reinforced composite materials have been the subject of intensive research because they offer the potential for substantially improved properties compared to currently used bulk materials. Their use could permit increased performance in many engineering systems. One of the systems that is limited by the capability of current materials is the turbojet engine. Designers would prefer to increase operating temperatures of such engines to increase efficiency and reduce pollution. Increased strength at elevated temperatures may be achieved with refractory-metal-wire - superalloy composites compared with superalloys. This in turn might permit an increase in turbine operating temperature.

Refractory-metal-wire - superalloy composites which have been investigated at a number of laboratories (refs. 1 to 5) have the potential of combining the high-temperature strength of a refractory metal with the oxidation resistance, toughness, and ductility of a superalloy. Several problems must be overcome, however, to achieve the desired combination of properties. Interdiffusion and reaction at the fiber-matrix interface can degrade fiber properties and thereby the composite properties. Also, tungsten, one of the principal refractory metals considered as a reinforcement material, loses much of its ductility below the ductile-brittle transition temperature, 150° to 370° C (300° to 700° F), for tungsten wire. For aerospace use, the high density of most refractory-metal alloys must also be accommodated. These problems have been recognized, and progress has been made in overcoming them. It is the purpose of this report to review the current status of development of refractory-wire - superalloy composites with a particular view toward their potential for application to turbine blades for advanced aircraft and land-based gas-turbine engines.

REFRACTORY-WIRE DEVELOPMENT

The need for refractory-alloy fibers with improved strength was recognized early in the superalloy composite program at the Lewis Research Center, and a continuing effort to fabricate and evaluate stronger alloy wire was initiated as part of the composite program. Alloys of molybdenum, tantalum, columbium, and tungsten have been fabricated into wire for use in composites as part of this program (refs. 6 to 10). The wire properties shown in figure 1 indicate the stress-density-ratio (stress/density) values for 100-hour rupture life at 1090° C (2000° F) for some of the wires developed as part of that effort. The data for 218 alloy lamp-filament wire and for conventional bulk superalloys are included for comparison. The high strength achieved for the wires developed is readily apparent with about a threefold stress/density advantage for the tungsten (W)-rhenium (Re)-hafnium (Hf)-carbon (C) alloy wire (W-4.1Re-0.38Hf-0.021C) over the 218 wire. The difference in stress/density between the W-Hf-C wire (W-0.33Hf-0.042C) and the W-Re-Hf-C wire is at least in part due to thermomechanical fabrication differences and off-optimum composition. The B88 columbium alloy wire is superior to the 218 wire at 1090^{o} C (2000^{o} F) and is primarily intended for use at temperatures below 1090^{o} C (2000^{o} F), where it has a potential advantage. The very high strength of these wires indicates a potential for achieving high composite properties where the fiber strengths can be realized within the superalloy matrix. Additional improvement in wire fabrication processing can be expected which should further increase strength and productivity at reduced cost. The refractory-metal alloys which were included in the wire development program had been developed for rod or sheet applications at higher use temperatures than currently proposed for refractory-wire - superalloy composites. The rupture properties of the wires in most cases were superior to those for sheet, rod, or foil at the composite use temperatures. It is believed, however, that there is considerable opportunity for further refractory-alloy composition development, which coupled with improved thermomechanical fabrication processing, can produce wire with strength optimized for use in superalloy composites.

COMPOSITE RUPTURE STRENGTH

Composites with excellent rupture strength can be achieved if wire properties such as those in figure 1 can be realized within the superalloy matrix. However, except for a few systems, metal fibers react with metal matrices and thereby cause varying degrees of property loss. Interdiffusion, reaction, and recrystallization can reduce wire strength and ductility. Therefore, control of matrix-fiber interaction is necessary during composite fabrication and throughout the service lifetime. Diffusion-barrier coatings on the wire are a potentially effective way to achieve such control. Unfortunately, techniques attempted in the past have not resulted in reproducible and successful barrier coatings for refractory-alloy wires. Since diffusion barriers are not presently available, alternative methods have been used to control reactions. Thus, specific fabrication processing variables have been selected to minimize the extent of interaction for most refractory-wire - superalloy composite systems. Many investigators (refs. 3 and 11 to 13) have used solid-state processing, either powder metallurgy or foil-wire compaction. Other investigators have used liquid-phase or casting techniques (refs. 2, 4, and 14), and some attempts have been made to limit matrix-fiber reaction.

The refractory-wire - superalloy composite program at the Lewis Research Center used a combination of factors, including fabrication processing, matrix alloy composition, and fiber diameter, to control matrix-fiber reaction (refs. 15 and 16). The fabrication process was developed to limit reaction during composite fabrication, while matrix composition and fiber diameter were selected to control service exposure reaction. A slip-casting - hot-pressing process was used to take advantage of the lower diffusion rates of solid-state sintering rather than the more damaging liquid-phase methods. Furnace sintering was conducted in a hydrogen atmosphere at a relatively low temperature, 815° C (1500° F), to remove surface impurities on the powder and to partially densify the body. Removal of impurities was intended to reduce the extent of reaction from rapidly diffusing surface contaminants. Two-stage hot pressing was used to obtain as dense a body as possible before exposing the composite to high temperature because the higher density body would have lower diffusion rates than a porous body. Matrix alloy compositions were selected to reduce the tendency for solute diffusion into the fiber. These alloys contained high weight percentages of refractory metals to reduce diffusion penetration kinetics and recrystallization. Titanium and aluminum additions to the matrix were made to form intermetallic compounds which could further reduce the diffusion of nickel and increase matrix strength. The final step taken to maximize retained composite strength was to select the wire diameter so as to increase the size of the unreacted wire core. The depth of penetration of reaction is essentially the same for a 0.20-millimeter- (8-mil-) diameter fiber as for a 0.50-millimeter- (20-mil-) diameter fiber. Using larger diameter wire increases the percentage of unreacted fiber core. However, smaller diameter wires are usually stronger, so a balance must be achieved between the two effects. The larger diameter wire, 0.38- to 0.50-millimeter (15- to 20-mil), was superior for service times of 100 hours or more (ref. 15).

Composite specimens have been fabricated by using the techniques described, and data for several refractory-wire - superalloy composites are shown in figure 2. Data for conventional superalloys and directionally solidified eutectic composites are also included for comparison. The data are normalized for density variation to permit cross comparison. The nickel-base alloy nickel (Ni)-tungsten (W)-chromium (Cr)-aluminum (Al)-titanium (Ti) (Ni-25W-16Cr-2Al-2Ti) developed to reduce matrix-fiber reaction was used as the matrix for all three refractory-wire composites. The data for 218 wire composites and tungsten-thorium oxide ($W-2ThO_2$) wire composites (refs. 15 and 16) compare favorably with those for superalloys and eutectics.

The W-Hf-C wire composites contained wire recently produced as part of the continuing wire development program at Lewis. The W-Hf-C composite has a strength/density of about 2540 meters (100 000 in.) or over four times the value for superalloys and over twice the best published values for directionally solidified eutectics. This advantage in specific strength may be used to increase service life or operating temperature or both. The stress for 1000-hour rupture at 1090° C (2000° F) for the W-Hf-C composite (neglecting the density difference) was 414 meganewtons per square meter (60 000 psi) or about eight times that for superalloys and four times that for eutectics. This comparison was based on data obtained from composites containing wires without diffusion barriers. As such, composite data were influenced by matrix-fiber reaction. Matrix element diffusion into the wire caused about a 30-percent reduction in wire stress-rupture strength compared to that without matrix-fiber reaction. The reduction was attributed (ref. 15) to diffusion-triggered recrystallization of an outer layer of the wire. Based on limited metallographic data, diffusion-barrier coatings are expected virtually to eliminate such losses. A problem to be overcome is the development of methods to apply well-bounded barriers reproducibly and uniformly. The author is optimistic that barrier coatings will be achieved soon and this will serve to increase both strength and use temperature.

Figure 3 illustrates a projection of the properties that might be achieved with diffusion-barrier-coated refractory-alloy-wire composites and directionally solidified eutectics. The property plotted is density-normalized 1000-hour rupture strength at 1090° C (2000° F). The refractory-wire - superalloy composite strengths shown are from four to six times those for the eutectics. The composite data were calculated by using wire data from figure 1 and assuming negligible matrix strength contribution and a 5-percent loss in wire strength from fiber-matrix reaction. Such a reactivity loss could result from localized breakdown of the diffusion barrier. It is evident from the comparisons in figures 2 and 3 that refractory-wire - superalloy composites have excellent rupture strength and that there is potential for further increases. These comparisons also suggest that such composites have excellent potential for use in turbine blades at operating temperatures higher than those currently used.

IMPACT STRENGTH

Materials must display other properties in addition to high rupture strength to be suitable for turbine blade use. One such property is the ability to resist impact failure from foreign objects and fragments from failed components that may pass through the engine. The impact resistance necessary for turbine blades is not clearly related to laboratory impact data. Simulated engine tests with rotating components or actual engine service experience are necessary to fully prove a material for turbine blade application. The impact strength required for short stubby blades may be different than that for long thin blades. Experimental superalloys have been evaluated at the Lewis Research Center in engine tests with blades about 10 centimeters (4 in.) long. Some of these materials which displayed limited impact strength in pendulum impact tests were operated successfully as turbine blades in such engine tests. Alloys with miniature Izod pendulum test impact values less than 1.7 joules (15 in.-lb) have been successfully run as turbine blades (refs. 17 and 18). Based on this information, the value of 1.7 joules was taken as a minimum standard value for miniature Izod impact test data to indicate if a material has promise for further evaluation leading to turbine blade use.

Pendulum impact strength of refractory-wire - superalloy composites has been measured (refs. 16 and 19). Miniature Izod data obtained for composites over a range of temperatures are shown in figure 4(a). Charpy impact test data obtained for composites at 1090° C (2000° F) and for conventional superalloys at 870° C (1600° F) are shown in figure 4(b). The composites were slip-cast and hot-pressed from 218 lamp-filament wire and a matrix of the nickel alloy designed for compatibility (ref. 15). The miniature Izod impact strength values of the composite above the ductile-brittle-transition temperature (DBTT) of the tungsten wire, which is about 260° C (500° F), were well above the minimum standard for turbine blades. The Charpy test values for the composite at 1090° C (2000° F) were well above those for the conventional superalloys at their normal operating temperature in turbines. Thus, the composite impact values can be considered acceptable for turbine blade use above the DBTT of the tungsten wire, where plastic deformation of the wire can contribute significantly to the composite impact strength. At temperatures below the DBTT of the wire, the miniature Izod data for the as-hot-pressed composite were below the minimum standard. However, as shown in figure 5, the composite impact strength can be improved to meet or exceed turbine blade requirements. The room-temperature data of figure 5 show that the impact strength of the as-hot-pressed composite is below the minimum standard. Heat treatment for 100 to 250 hours at 1090° C (2000° F) or hot rolling the composite increased the room-temperature impact strength to values well above the minimum standard.

The improved impact strength was related (ref. 19) to improved matrix impact strength. Scanning electron micrographs of fracture surfaces showed increased bonding of matrix powder particles and evidence of plastic deformation of the matrix after rolling or heat treatment. Similar fracture micrographs of as-hot-pressed composite specimens showed much less bonding and very little matrix deformation. Secondary deformation of powder-metallurgy matrix composites can readily be accomplished by hot-forming in closed dies. However, it is expected that blade airfoils will be fabricated by using diffusion bonding of foil-wire monolayers. Excellent matrix toughness could be achieved by this method without the need for secondary fabrication.

OXIDATION RESISTANCE

Relatively few data have been obtained to determine the oxidation resistance of composites, and further research is necessary to evaluate this aspect more fully. Many of the data that have been obtained have been sufficiently encouraging to justify additional research. Oxidation data have been obtained for slow-moving furnace air exposure for times to 500 hours at temperatures of 1090° C (2000° F). No visible oxidation of the tungsten wire was found when it was protected by a few tenths of a millimeter of superalloy matrix (ref. 2). Similar results have been obtained (ref. 2) for composite specimens exposed to 1090° C air moving at 1.85 meters per second (6 ft/sec). When tungsten fiber ends were exposed to 1090° C air moving at 1.85 meters per second (6 ft/sec) for 100 hours, only a 2.8-millimeter (0.1-in.) length of the approximately 1-millimeter- (0.04 in.) diameter wire was oxidized. This very slight depth of oxidation below the surface of the exposed wire end is encouraging since it suggests that local defects in the protective matrix coating would not cause a large loss of fiber. Such defects in the coating can occur from blade fabrication processing or from foreign object damage during engine service. There remains the task of determining the oxidative behavior of composites when they are exposed to erosive high-velocity gas streams and cyclic temperatures that are typical of aircraft engine service. These conditions represent a more severe requirement than has been evaluated in laboratory tests to date, since temperature cycles can cause spalling of protective oxide films and the erosive scrubbing action of the high-velocity gas stream also removes material.

Oxidation protection will be a critical requirement in achieving composite turbine blade operating temperatures above 1090° C (2000° F). Superalloy compositions for the airfoil can be selected to provide ductility and erosion and oxidation resistance, particularly where fiber-matrix reaction control is provided by a diffusion barrier. For composites with uncoated wire, the matrix composition can be varied to provide an oxidation-resistant outer layer and a more compatible composition near the fibers.

MECHANICAL AND THERMAL FATIGUE

A limited number of high-cycle fatigue studies of refractory-wire - superalloy composites have been conducted. Additional laboratory data are needed to evaluate the quantitative behavior of the materials and to estimate their potential for turbine blade service. High-cycle fatigue resistance of Hastelloy X and Nimocast 258 reinforced with tungsten wire was improved relative to unreinforced Hastelloy X and Nimocast 258 (refs. 2 and 20). However, tungsten-wire reinforcement did not increase the fatigue strength of Nimocast 713C (ref. 14). The lack of improvement in the fatigue strength (ref. 14), in contrast to the results of reference 2 and 20), was attributed to low resistance to crack propagation in the relatively brittle 713C alloy matrix and the poor crack stopping ability of the large-diameter wires used for the investigation of reference 14. The small number of large-diameter, 0.13-centimeter (50-mil), wires used (ref. 14) would be expected to be less effective as a crack stopper than the smaller diameter, 0.025-centimeter (10-mil), wires used in the investigations of references 2 and 20. It should also be emphasized that increased matrix ductility which would probably increase resistance to crack initiation also would be advantageous in enhancing fatigue resistance. Thermally induced low-cycle fatigue requirements may be critical for aircraft turbine blade application of composites. Stresses may be generated by the thermal gradient between different portions of the blade during transient temperature operation as well as by the thermal expansion difference between the refractory wire and the superalloy matrix. It will be necessary to use ductile matrix materials which hopefully can relieve such induced stresses by plastic deformation. Some variation in results was obtained for the very few data points published for thermally cycled refractory-wire-composite specimens (refs. 4 and 14). Matrix cracking has been observed with cylindrical specimens of tungsten-wire - cast Inco 713C composites heated in fluidized beds. Similar specimens containing 20 volume percent wire (1- or 1.3-mm diam) showed no cracking (ref. 4) after several hundred fluidized bed heating cycles between 550° and 1050° C (1020° and 1920° F). While matrix cracks were observed after as few as two thermal cycles (ref. 14), tensile tests conducted on specimens thermally cycled and cracked showed no strength loss. The relatively brittle cast 713C alloy which cracked in thermal fatigue also showed poor resistance to mechanical fatigue (ref. 14). More ductile matrix alloys may be more resistant to crack propagation and provide better thermal and mechanical fatigue resistance.

Further testing is necessary to indicate the seriousness of this failure mode and to evaluate possible corrective measures. Ability to resist thermal fatigue may be critical for aircraft engine service, but may be of little concern for blades used in gas-turbine-powered electric-power-generation systems. Continuous or very long time periods of operation are the norm for base load power generating plants. These advanced power systems also require very high turbine-inlet temperatures, and refractory-wire - superalloy composites may be well suited for such service. This aspect will be discussed more fully in the LAND-BASED POWER GENERATING GAS-TURBINE ENGINE APPLICATION section of this report.

DENSITY

A persistent concern held about tungsten-wire - superalloy composites has been that there is a weight penalty associated with their use despite the superior strength/density values of the material compared with superalloys. However, the turbine blade weight for a solid blade of tungsten-wire - superalloy composite need not exceed that for a similar blade made from a conventional superalloy if reasonable measures are taken in design and fabrication of the composite. Two variables can be used to overcome the high density of the refractory-alloy wire. The fiber content can be varied along the blade span so as to tailor strength to that needed, and the blade airfoil thickness near the base can be slightly reduced compared with a superalloy blade because of the improved strength/density properties of the composite. Blades with varying fiber content can be fabricated using conventional diffusion bonding techniques. Fiber-free superalloy foil and monolayer superalloy matrix composite tape, each cut to the appropriate contours, can be stacked and bonded in closed dies.

The following discussion indicates the possibility of achieving superalloy composite blade densities comparable to those for conventional superalloys while increasing the allowable turbine operating temperature several hundred degrees.

Fiber content variation, or selective reinforcement, can reduce the average fiber content significantly. Sample blade density calculations made to illustrate the effectiveness of selective reinforcement are shown in table I. Calculations were made for both uncoated and diffusion-barrier-coated refractory-wire composites. The airfoil matrix alloy for the uncoated wire was the NASA nickel-base alloy developed for compatibility with tungsten wires. A 30-percent wire strength loss was assumed to occur from matrix-fiber reaction. This value is about that observed for the composite data obtained thus far in Lewis Research Center studies (refs. 15 and 16). A conventional superalloy, IN 100, was selected as the matrix for the diffusion-barrier-coated-wire-composite calculations. A 5-percent wire strength loss was assumed for the wire with a diffusion barrier. Blade bases of both composites were assumed to be of IN 100 alloy. Calculations of composite blade fiber content and density were made for a range of blade use temperatures.

The calculations were made for a standard solid blade geometry and the centrifugally induced stresses that would be generated at about midspan in the airfoil of such a blade. Midspan stresses in a typical solid superalloy blade were taken (ref. 1) as a range from 103 to 138 meganewtons per square meter (15 000 to 20 000 psi). Since the stresses generated in rotating blades are density dependent, a stress/density value was used. The stress/density value at blade midspan for a typical superalloy with a density of 8.3 grams per cubic centimeter (0.3 lb/in.^{3}) would range from 1270 to 1695 meters (50 000 to 66 700 in.). The stress/density value used for the calculations was taken as 1525 meters (60 000 in.), about the middle of that range. The density values in table I for varied-fiber-content composite blades ranged from 8.8 to 10.2 grams per cubic centimeter (0.32 to 0.37 lb/in.^{3}). High-strength superalloys which have about a 980° C (1800° F) use temperature limit as turbine blades have densities as high as 8.97 grams per cubic centimeter (0.325 lb/in.^{3}) (ref. 4). Thus, the blade density values in table I for the varied-fiber-content blades ranged from within the density range for superalloys to about 20 percent above that for superalloys. The relatively low density values for the composites were possible because the average fiber content was 15 volume percent or less. The maximum fiber content at any one cross section of the blade was less than 35 volume percent for all four composite calculations. The low average fiber content means that little reduction in blade airfoil thickness near the base is required to reduce overall blade weight to values equal to those for superalloys.

According to blade designers, reductions in blade thickness or taper are aerodynamically acceptable and may be advantageous. Blade geometry design is a compromise between aerodynamic and material considerations. Material limitations sometimes lead to blade thicknesses near the airfoil base that result in aerodynamic penalties and usually result in tapers greater than are aerodynamically necessary. Material with higher stress/density values, such as the refractory-wire - superalloy composites, may permit a better compromise in blade geometry design which can produce a blade of equivalent weight and at the same time may permit its use at higher temperatures.

ADVANCED-AIRCRAFT GAS-TURBINE BLADE APPLICATION

Figure 6 shows the possible aircraft engine blade use temperature range of refractory-wire - superalloy and directionally solidified eutectic composites along with those for superalloys based on the data from figures 2 and 3. Rupture strength data for 1000-hour life have been normalized for density. The horizontal band represents a range of stress/density values that might be required for turbine blades in advanced-aircraft gas-turbine engines. The blade use temperature range of the refractory-wire composites is 1150° to 1260° C (2100° to 2300° F) or about 165° to 280° C (300° to 500° F) above that of superalloys. The eutectic composites had 40° to 80° C (70° to 150° F) higher use temperatures than the superalloys. The lower portion of the refractory-wire composite use temperature band can be achieved with uncoated-wire-reinforced composites, while the higher portion will probably require diffusion-barrier-coated wire.

The increased use temperature which may be possible through the application of solid blades of refractory-wire - superalloy composites is significant; however, turbine engine designers want to take advantage of the higher efficiencies gained by going to flame temperatures over 1650° C (3000° F). Turbine blade cooling will be required to operate with any superalloy or superalloy composite blades at these very high flame temperatures. Several blade types have been studied for such cooling. Convection-cooled blade designs are simple and more readily fabricated, but require higher cooling airflow rates because of lower cooling efficiency. Film-cooled blades are more complex but require less cooling airflow to reach tolerable blade material temperatures. However, as can be seen in figure 7, from reference 21, operation at turbine blade material temperatures of 1150° to 1200° C (2100° to 2200° F) with a convection-cooled blade might permit turbine-inlet temperatures over 1650° C (3000° F). Further, it can be seen in figure 7 that cooling flow requirements for such a convection-cooled composite blade would be equal to or less than those required for superalloy blades film-cooled at 980° C (1800° F), about the operational limit of superalloys.

Previous discussion has suggested that refractory-wire - superalloy composites have potential for operation at 1150° to 1200° C (2100° to 2200° F). It may thus be possible to use convection-cooled composite blades at this higher operating temperature and thereby gain the benefit of the simpler blade design and fabrication while maintaining an equal or lower cooling flow. Furthermore, aft stages of the turbine might be operated without cooling because of the higher temperature operating limit of the composites. This can reduce cooling air flow requirements, engine complexity and weight, and increase engine performance.

LAND-BASED POWER GENERATING GAS-TURBINE ENGINE APPLICATION

Large turbine engines have been proposed for land-based electric power generation systems (ref. 22). Such systems are needed to satisfy the demands for additional power with reduced air and thermal pollution and with stable or reduced cost. A promising system proposed for such needs is a base load generating plant combining a gas-turbine and a steam-turbine generator. One of the simpler cycles of this type is shown schematically in figure 8. Hot exhaust gases from a gas-turbine generator system are used to heat steam which powers a steam-turbine generator system. The combined cycle efficiency is greater than that possible for current or projected steam plants alone. The greater system efficiency of the combined or COGAS system will more than offset the cost of removing pollutants from the fuel before combustion. However, the increased cycle efficiency is possible only with the high operating temperatures indicated for the second- and third-generation systems shown in figure 9 (ref. 22). Refractory-wire composites are potentially useful as turbine blade materials for such an increase in use temperature.

Several operational factors facilitate application of the composite to a power generating turbine over an aircraft turbine. Because thermal cycling is infrequent, the possibility of thermal fatigue failure is almost eliminated, and oxidation protection is easier. Thermal-cycle-induced spalling of protective oxide films, a major accelerator of oxidation penetration rate, would thus be greatly reduced.

Also, there is much less restriction on blade weight since increased turbine disk size and weight incur very little penalty for land-based units. The high weight limit means that higher fiber contents can be used since specific strength or strength/density increases with fiber content. It is important that higher strength/density values are possible for the composites that might be applied to land-based turbine blades, because the system life expected is 30 000 to 100 000 hours. This long service life is accumulated with infrequent opportunity for inspection and maintenance, which increases the need for reliability.

Thus, refractory-wire - superalloy composites appear to have potential for use as turbine blades which can be operated at increased use temperature for both aircraft and land-based turbine applications.

BLADE FABRICATION AND COST

Blade fabrication process development and costs are important aspects to consider in reviewing the potential of a material. Evaluation of various fabrication processes for refractory-wire composites is the subject of a current Lewis Research Center program. Since blades have thus far not been made in the program, this discussion must be based on probable fabrication methods. The most probable fabrication technique to be adopted for solid composite turbine blade airfoils is one that has already been developed for aluminum and titanium matrix compressor blades: diffusion bonding of monolayer tapes containing fiber and matrix. Higher bonding temperatures than those for aluminum and titanium matrix compressor blades will be required, but no other major differences are expected to complicate fabrication. Titanium matrix blades are diffusion-bonded at about 870° C (1600° F), whereas about 1090° C (2000° F) will be needed for the superalloy matrix.

The cost of production quantities of titanium-matrix - silicon carbide filament compressor blades produced by diffusion bonding has been estimated at twice to four times that for conventional forged and machined titanium blades. The cost of filament for such a composite blade was $1300 to $2200 per kilogram ($600 to $1000 per lb) and represented a large portion of the total blade cost estimate. It is expected that filament cost will be reduced. The above estimate can be used to arrive at possible refractory-wire - superalloy blade costs. High-strength tungsten-alloy wire such as the W-Hf-C wire was developed in research contracts, and no production cost data are available. However, it is estimated that a cost of about $65 to $110 per kilogram ($30 to $50 per lb) might be achieved for production quantities of 0.4- to 0.5-millimeter-diameter wire. Based on this fiber cost, the total cost of a refractory-wire - superalloy blade could be similar to that of the titanium - silicon carbide (SiC) composite blade. The refractory wire cost would be less than that for the silicon carbide filament, but the diffusion bonding costs would be higher for the superalloy matrix than for the titanium. Thus, an estimate of two to four times the cost for a conventional forged blade seems reasonable.

Lower costs may be achieved for solid blades if the superalloy matrix can be cast into an appropriate array of fibers. Hollow cooled blades would probably be fabricated by separately producing and then joining the outer shell and the strut. These blades would be more expensive, and would cost perhaps twice as much as solid blades.

CONCLUDING REMARKS

This review suggests that refractory-fiber - superalloy composites have demonstrated sufficiently high strength and impact values to have considerable potential for application to advanced turbine engine blades. The data obtained thus far indicate a potential for increasing the turbine blade material operating temperatures to 1200° C (2200° F) and above. However, few data have been obtained thus far as to their oxidation, erosion, and thermal and mechanical fatigue resistance. Additional testing is necessary to demonstrate the performance of refractory-wire - superalloy composites under all of these imposed environmental and loading conditions to indicate where improvements may be needed. The excellent mechanical properties already obtained and the promising potential for increased turbine life and operating temperatures justify the effort to complete the evaluation of these materials. A number of generalizations can be made:

(1) Successful developments and application of refractory-wire - superalloy composites to aircraft gas-turbine blades could permit blade use temperatures as high as 1150° C (2100° F) without diffusion-barrier-coated fibers and as high as 1260° C (2300° F) with diffusion barriers. Oxidation protection for the blade airfoil is a critical requirement for such an increase in operating temperatures, particularly for aircraft use where temperature cycling causes spalling of protective oxide films. The composites have equal or better potential for application to land-based power generating gas turbines operated at increased use temperatures because limited thermal cycling of the system eases oxidation and thermal fatigue conditions and lessens the need for low density.

(2) Density-normalized 1000-hour stress-rupture values at 1090° C (2000° F) for tungsten-fiber - superalloy composite specimens were over four times those for conventional superalloys and over twice those for the best published values for directionally solidified eutectics. Further increases in the strength of refractory-wire - superalloys are possible to increase this advantage. The potential strength of refractory-wire - superalloy composites using diffusion-barrier-coated wire could be from four to six times the density-normalized values for directionally solidified eutectics at 1090° C (2000° F).

(3) Turbine blade material temperatures of 1150° to 1200° C (2100° to 2200° F) for a relatively simple convection-cooled composite blade might permit gas-turbine engine operation at turbine-inlet temperatures over 1650° C (3000° F). Cooling airflow requirements for such a convection-cooled blade operating at 1150° to 1200° C (2100° to 2200° F) are lower than those for superalloy blades film-cooled to 980° C (1800° F), about the operational limit of superalloys.

(4) Turbine blade weight for a solid blade of tungsten-wire - superalloy composite need not exceed that for conventional superalloys if reasonable measures are taken with the composite. Two variables can be used to overcome the high density of the refractory fiber. The fiber content can be varied along the blade span so as to tailor strength to that needed, and the solid blade thickness can be slightly reduced near the base as permitted by the improved strength/density properties of the composite. Selective re-

inforcement could reduce the average fiber content for a standard solid blade geometry to about 15 volume percent or less. The low fiber content means that little reduction in taper is required to reduce the overall blade weight to values equal to those for equivalent solid superalloy blades.

(5) Very few data have been obtained for failure mechanisms such as oxidation, fatigue, and erosion. The limited data obtained indicate sufficient promise to justify further research to develop the composite system. The need for oxidation protection at 1090° C (2000° F) and above has been indicated.

(6) Matrix cracking has been observed for some brittle cast-superalloy-matrix composites thermally cycled to simulate aircraft engine operation. Further testing is necessary to investigate the seriousness of this problem. The matrix must exhibit sufficient ductility to resist low-cycle fatigue failure generated by thermal expansion mismatch between matrix and fiber in order to be suitable for aircraft engine service. This failure mode would be of little concern for refractory-wire - superalloy composite blades used in advanced electric-power-generation systems where continuous or long-period operation is the norm. These advanced power systems also require very high turbine-inlet temperatures for efficient operation, precisely the advantage afforded by refractory-wire - superalloy composites.

(7) Refractory-wire - superalloy composites can be fabricated to display pendulum impact test values well above minimum requirements for turbine blades. Charpy and miniature Izod impact test values for hot-pressed composites compare favorably with those for superalloys at temperatures above the ductile-brittle-transition temperature of the refractory fiber, about 260° to 370° C (500° to 700° F) for the tungsten wire used in the composites. Impact strength values of composites adequate for turbine blade applications below the fiber ductile-brittle-transition temperature have been obtained for tungsten-wire - superalloy composite specimens fabricated by using techniques suitable for turbine blades.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 26, 1972,
134-03.

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TABLE I. - EXAMPLES OF BLADE DENSITY CALCULATED BY USING SELECTIVE REINFORCEMENT WITH STANDARD SOLID BLADE GEOMETRY

[Calculation based on 1525-m (60 000-in.) stress/density in middle of blade span (critical zone) for 1000-hr rupture failure.]

Composite		Use temperature		Blade density		Maximum wire content, vol. %	Average wire content, vol. %
Matrix	Wire	^{o}C	^{o}F	g/cm^3	$lb/in.^3$		
Nickel-base superalloy	Uncoated W-Re-Hf-C	1090 1150	2000 2100	9.8 10.2	0.35 .37	26 34	11 15
IN 100 superalloy	Diffusion-barrier-coated W-Re-Hf-C	1150 1200	2100 2200	8.8 9.4	0.32 .34	18 27	7 12

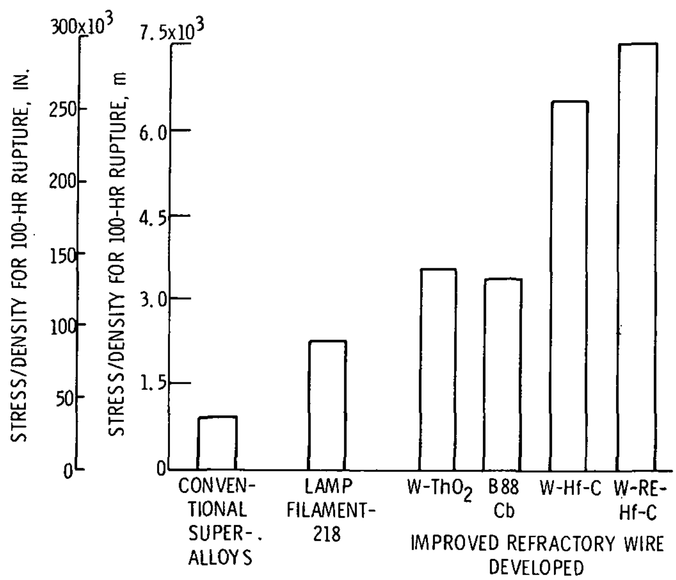


Figure 1. - 100-Hour stress-rupture properties of refractory alloy fibers at 1090° C (2000° F).

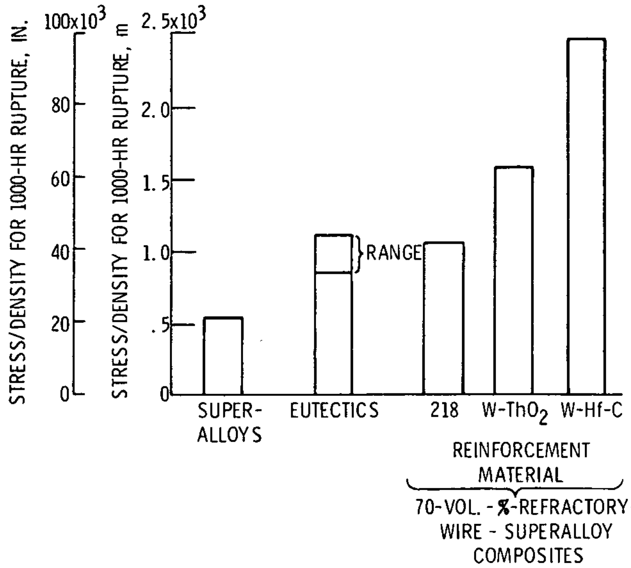


Figure 2. - 1000-Hour stress-rupture properties of refractory-wire - superalloy composites at 1090° C (2000° F).

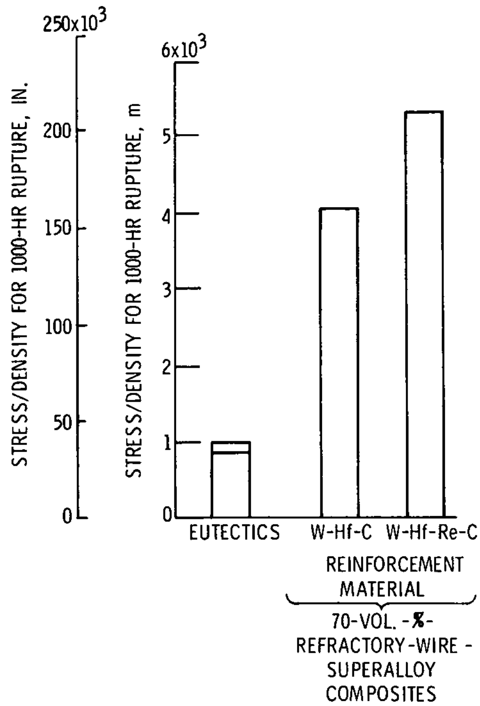
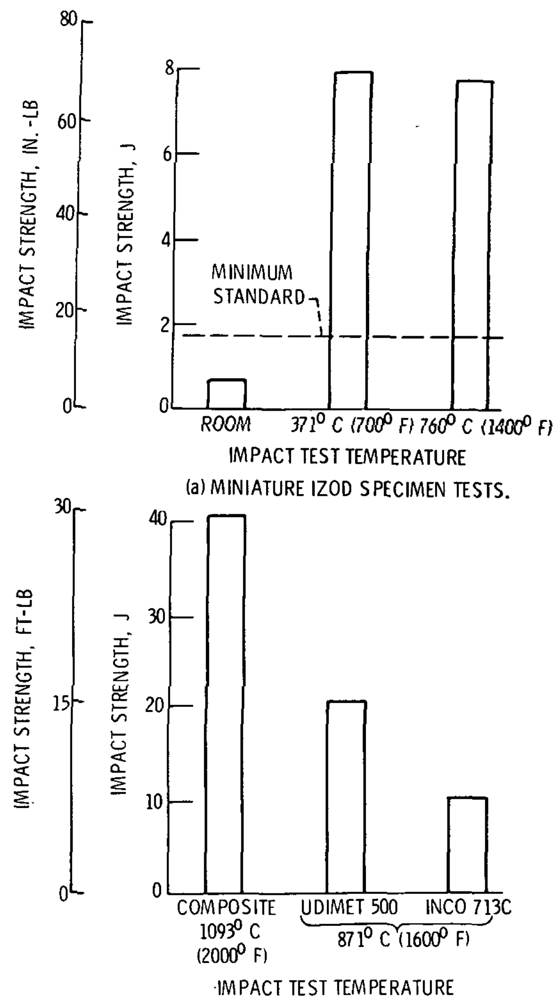


Figure 3. - Projected 1000-hour composite rupture properties with diffusion barriers at 1090° C (2000° F).



(a) MINIATURE IZOD SPECIMEN TESTS.

(b) CHARPY SPECIMEN TESTS.

Figure 4. - Impact strength of tungsten-lamp-filament-wire - superalloy composites for several test temperatures. Composite 60 volume percent wire.

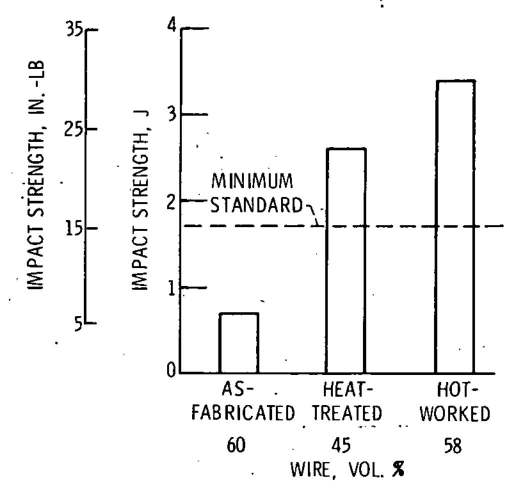


Figure 5. - Improved room-temperature impact strength of tungsten-lamp-filament-wire - superalloy composites. Miniature Izod tests.

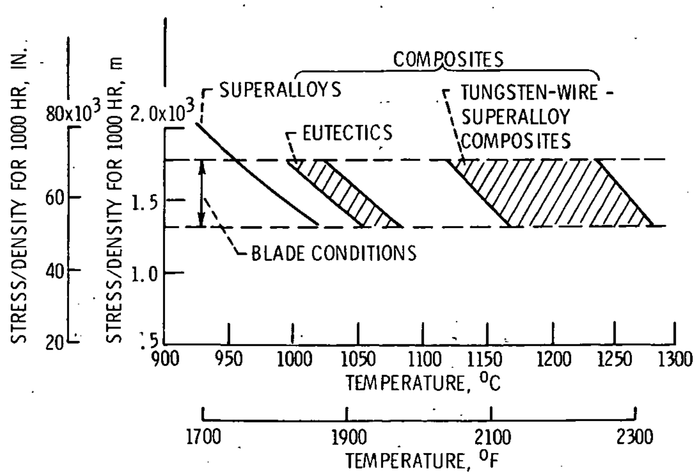


Figure 6. - Potential blade use temperatures for 1000-hour life.

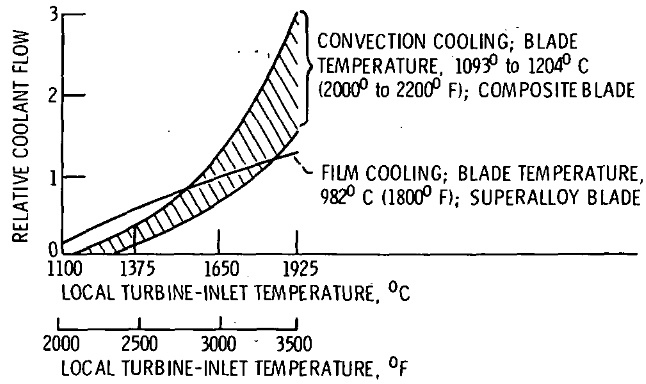


Figure 7. - Effect of blade temperature on cooling airflow requirements.

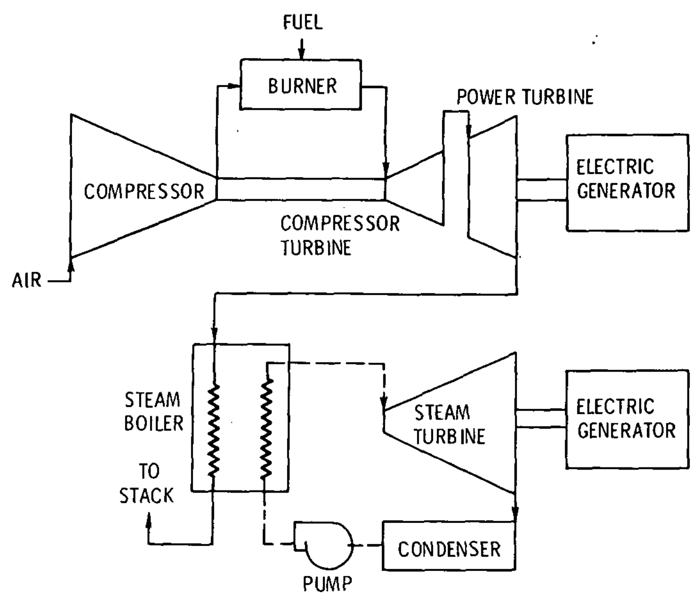


Figure 8. - Schematic diagram of waste heat recovery COGAS electric power generating system (ref. 22).

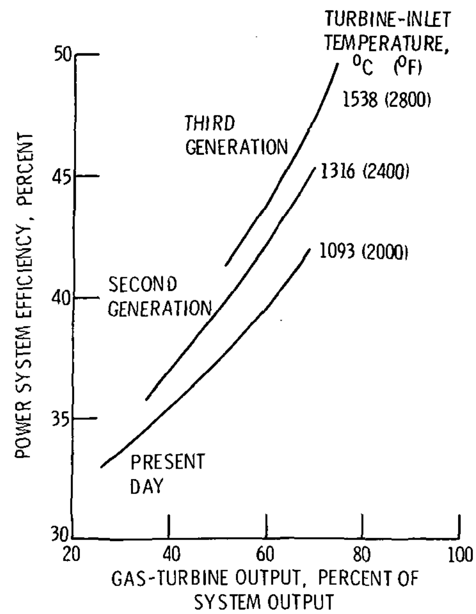


Figure 9. - Effect of turbine-inlet temperature on COGAS system efficiency.

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