Directional Structures for Advanced Aircraft Turbine Blades

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In order to achieve the performance and durability requirements of advanced gas turbine engines, high-pressure turbine blade materials with directional structures will be required. Directional structures can be obtained by liquid-solid (solidification) or solid-solid (recrystallization) reactions, or by composite fabrication techniques. Currently, directional solidification is used to produce columnar-grained superalloy turbine airfoils. This production process can be modified to provide single-crystal superalloys or directionally solidified eutectic turbine blades. Directional superalloy structures also can be obtained by a solid-state recrystallization process, referred to as directional recrystallization. In addition, directional composite structures are fabricated by reinforcing a superalloy matrix with high-strength refractory metal wires. These five directional turbine blade materials are compared for use in advanced gas turbine aircraft engines. The present status of each advanced material is reviewed, and the advantages and limitations of each is assessed.

Introduction

THE performance and efficiency of the aircraft gas turbine engine, like all thermal engines, is a direct function of the maximum cycle temperature. This is the prime motivation behind the continuous search for turbine blade materials capable of operating at increasingly higher temperatures in the high-pressure turbine section of the aircraft gas turbine engine. The increase in turbine inlet temperatures and the accompanying increase in turbine blade metal temperature with time is shown in Fig. 1.

High-pressure turbine blades, because of the rigorous combination of temperature, stress, and atmosphere in which they are required to operate, usually are the limiting component in the engine. Nickel-base superalloys are a class of materials which have been found, over the past 30 years, to possess the optimum combination of properties required to withstand this demanding environment. Continued improvements in metal temperature capability, using the historical approach of adding additional alloying elements for increased strength and metal temperature capability, appear to have reached the point of diminishing returns. Replacement of nickel-base superalloys with another elevated temperature system (e.g., columbium or chromium-base alloys), which would permit the traditional approach of alloying for increased properties, has failed to materialize, and efforts in this direction have all but ceased because of the known difficulties with these other alloy systems. Therefore, we are faced with the need to obtain further property improvements via a new approach from the nickel-base superalloys. Directional structures represent such an approach, wherein existing high-strength nickel-base superalloys, or modifications of these, are processed to orient the material in such a manner as to place the major blade stress axis parallel to the strong direction of the material. The increase in strength as a result of microstructural alignment may be caused by elimination of a weak point in the structure, such as the transverse grain boundaries in superalloys, or by the presence of an aligned high-strength phase in the microstructure, as in eutectics and wire-reinforced superalloys.

Directional structures can be achieved by three processing techniques: 1) liquid-solid phase transformation (solidification), 2) solid-solid transformations (recrystallization and grain growth), and 3) artificial composite fabrication techniques. In the case of superalloys, the liquid-solid transformations rely on the preferred dendritic growth direction of cubic metals, which places the low modulus [100] crystallographic orientation parallel to the direction of solidification.[1-3] Directional solidification is used to produce: 1) columnar-grained superalloys with grains aligned parallel to the growth direction or major stress axis, and therefore eliminates grain boundaries normal to the principal stress direction; 2) single-crystal superalloys, which have no grain boundaries, made by placing a grain filter in the solidification path; and 3) eutectics, which solidify as a structure with finely aligned phases, consisting of a strong reinforcing phase in a superalloy matrix (Fig. 2).

Solid-state transformations, called DR (directional recrystallization) or ZAP (zone aligned polycrystal), rely on obtaining aligned grains, which eliminate grain boundaries aligned transverse to the principal stress direction, by recrystallization and grain growth in a thermal gradient. The preferred superalloy structure in this case usually has a different orientation, with a higher modulus than that obtained by the directional solidification process. The last method for producing directional structures uses conventional composite fabrication techniques, wherein high-strength refractory

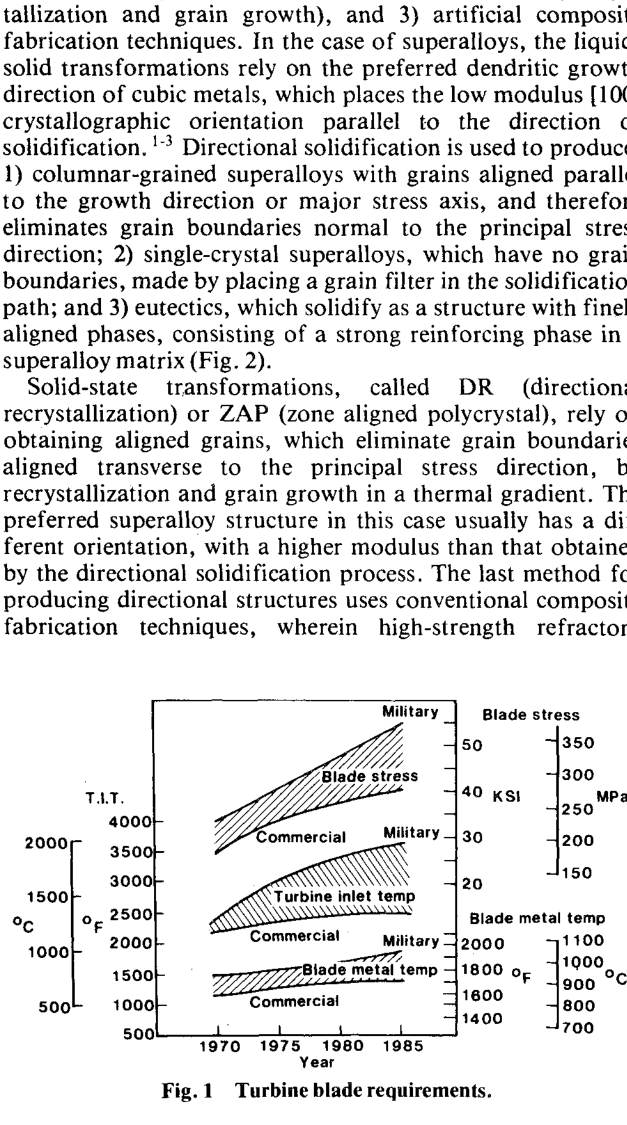

Fig. 1 Turbine blade requirements.

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metal wire reinforcement is embedded in a superalloy matrix. This technique does not align a preferred crystallographic orientation or grain structure, but achieves its directionality from the macroscopic alignment of the high-strength refractory metal wires.

Processing

Directional Solidification

Directionally solidified (DS) structures achieve their alignment by passing the solidification front through a thermal gradient.[4,5] Figure 3 shows a typical arrangement used to produce directionally solidified turbine blades. Single-crystal superalloys are cast using this technique, with the introduction of a grain filter between the turbine blade and chill plate, to permit only a single aligned grain to grow into the blade casting.[4] Directionally solidified eutectic alloys require planar front growth conditions, as opposed to columnar-grained and single-crystal superalloys, which grow by dendritic growth.[6,7] The solidification parameters, such as the thermal gradient (G) at the liquid-solid interface and growth rate (R), or rate at which the liquid-solid interface moves are more rigorous for the planar front directional solidification required for eutectics, as shown in Fig. 4, which defines the solidification parameters required for the various directionally solidified structures. The particular G/R ratio required to achieve planar front growth to properly align a eutectic (referred to as the critical G/R ratio) depends on the particular eutectic alloy system. Critical G/R ratios vary from values similar to those for dendritic superalloy growth to very demanding conditions, which eliminate consideration of these systems for practical applications.[8]

Directional Recrystallization

The directional recrystallization process starts with either oxide dispersion strengthened or conventional prealloyed superalloy powders, which are consolidated and given a small, but critical, amount of deformation to cause them to recrystallize[9-11] (see Fig. 5). The recrystallization process is carried out in a thermal gradient to produce high-aspect-ratio grains, as a result of post-recrystallization grain growth, which are aligned in the direction of recrystalization. Simple nickel-base alloys provide a [100] texture, whereas more highly alloyed superalloys may display a [110] texture. Iron-based FeCrAlY-type alloys have also been evaluated and result in a [110] texture.[12] In order to obtain shaped components, such as a turbine blade, the geometrical configuration is introduced into the material prior to passing it through the thermal gradient to minimize excessive metal removal costs. Complex air-cooled turbine blades made with this technique require sophisticated fabrication processing. The elongated grain structure obtained by heat treatment of a sample oxide dispersion strengthened alloy is shown in Fig. 6.

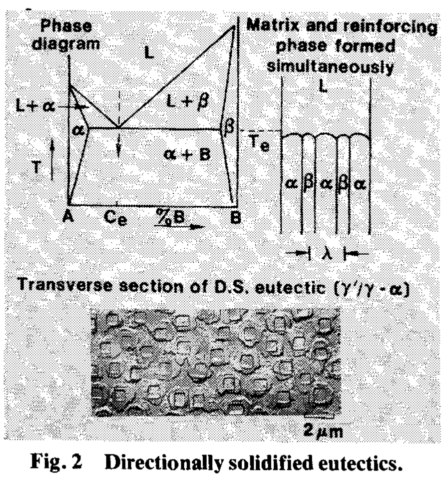

Fig. 2 Directionally solidified eutectics.

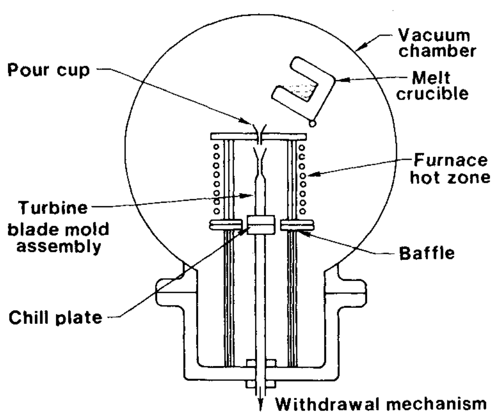

Fig. 3 Schematic of directional solidification of turbine blade.

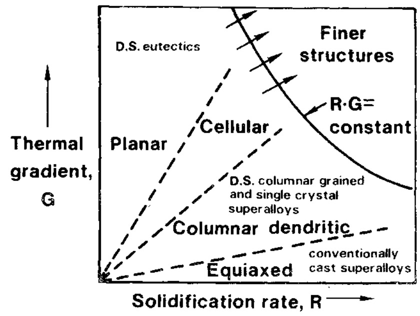

Fig. 4 Schematic of rate-gradient effects on grain shape and the refining of microstructures by high cooling rates.

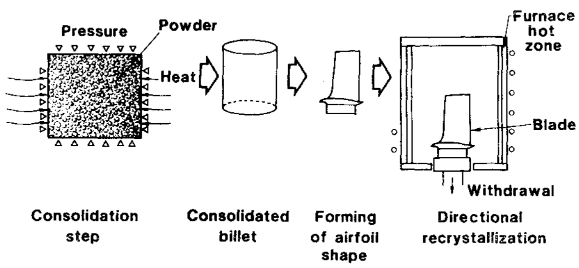

Fig. 5 Schematic of processing of directionally recrystallized superalloys and oxide dispersion strengthened alloys.

Wire-Reinforced Superalloys

Composites consisting of refractory wires within a superalloy matrix have been prepared by both casting and powder metallurgical methods.[13,14] In order to limit matrix-fiber reaction during composite fabrication, the powder metallurgical approach appears preferable. The use of a monolayer tape consisting of alloy foils and refractory wires, roll bonded, has been suggested[15] as the best approach to form composite elements from which structures could be constructed. The fabrication technique used here is similar to that used to prepare composite airfoils for lower temperature aircraft structural applications, and a schematic of the processing steps is shown in Fig. 7. As only simple basic shapes have been made, detailed processing techniques have not yet evolved. Graded wire reinforcing layers have been suggested, so that the high-density refractory wires can be placed only where necessary. The transverse microstructure of a tungsten-wire-reinforced FeCrAlY alloy, prepared from cross-plied tapes, is shown in Fig. 8.[16]

Material Properties

Nickel-base superalloys, as used currently for turbine blades in aircraft gas turbine engines, represent a compromise between critical properties. Any advanced material that offers potential property advantages in one or several specific properties must do so without compromising the other properties necessary for successful turbine blade utilization. If we improve one property the others required for turbine blade application can become limiting and prevent the new material from achieving the benefits attributed to it based upon improvement of a single critical property.

The critical properties necessary for successful application of an advanced turbine blade material are: 1) creep (rupture) strength and ductility, 2) thermal fatigue resistance, and 3) oxidation/hot corrosion resistance. With directional structures, one must be concerned with properties as a function of the direction in the material in which they were measured. In many cases, properties in the transverse direction (90° from principal direction) are limiting and, therefore, critical to the application of a directional turbine blade material. The limiting critical property and direction depend upon both the directional material chosen and the particular application. First-stage high-pressure turbine blades are extensively air cooled, and thermal fatigue often is the limiting property. Second-stage turbine blades are exposed to a lower temperature environment requiring less cooling air, but are more highly stressed, and creep strength usually is the limiting property. For specific engine applications, oxidation/hot corrosion resistance may plan a key role in dictating the useful life of some aircraft turbine blades.

Creep Strength and Ductility

Improved creep strength can be translated into increased temperature capability (at a fixed lifetime and stress), increased stress capability (at a fixed temperature and lifetime), increased life, or any combination of these. This translates to increased engine performance (thrust), fuel consumption, durability, or some combination of these benefits, depending upon how the improvement in turbine blade creep strength is used.

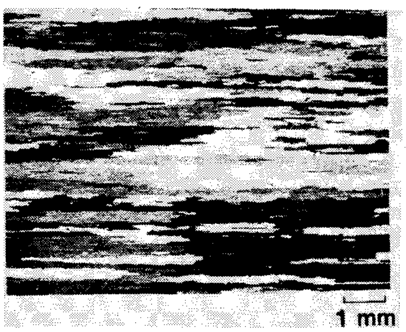

Fig. 6 Elongated grain structure in heat-treated inconel alloy MA 753 (picture courtesy of J. S. Benjamin, INCO).

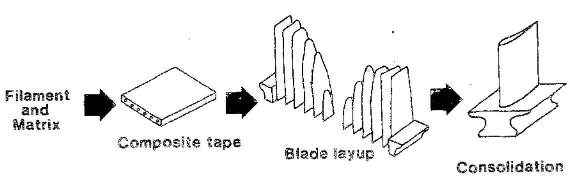

Fig. 7 Processing steps for tungsten-wire-reinforced superalloy composite turbine blade.

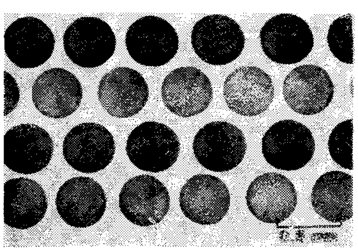

Fig. 8 W-fiber-reinforced FeCrAlY alloy. Fibers arranged in cross ply (±15°). (Picture courtesy of W. D. Brentnall, TRW).

Figure 9 is a comparison of 100-hour rupture strength parallel to the principal blade axis for directional structures. Creep data on all of the advanced directional materials are not available, and so we must compare these materials on the basis of rupture strength, which often correlates well with creep strength. Columnar-grained and single-crystal directionally solidified superalloys have superior strength when compared to conventionally cast superalloys.[4,5] This is because of the elimination of grain boundaries perpendicular to the major stress axis. Single crystals owe part of their strength improvement to their increased melting temperatures and the ability to solution heat treat them at higher temperatures, as well as to compositional modifications not possible with columnar-grained or conventionally cast superalloys. Directionally recrystallized superalloy structures, like the columnar-grained directionally solidified structures, benefit by the removal of transverse grain boundaries.[17] In addition, the wrought directionally recrystallized structures benefit from the more homogeneous microstructure, which results from the use of rapidly solidified prealloyed powder as a starting material, as well as the increased homogeneity of a wrought vs cast structure. These two directional superalloy structures with aligned grains are anticipated to have similar creep strengths. The directionally recrystallized, oxide dispersed strengthened superalloys exhibit, as a class, a somewhat lower intermediate temperature strength than do the comparison alloys, but show excellent strength at the highest temperatures as a result of the fine oxide particle dispersion. For complex air-cooled turbine blade applications, the strength advantage of advanced materials must be available over the entire range of turbine blade temperatures, i.e., at root attachment temperatures such as 1400°F, as well as at the higher airfoil temperatures. Oxide dispersion strengthened alloys have exhibited strength improvements primarily at the higher airfoil temperatures, and may require bonded conventional superalloy roots if their full potential is to be achieved. As shown in Table 1, these alloys have exhibited creep ductilities lower than those obtained with conventionally cast superalloys. As a consequence, their usable design strengths will be reduced.

Eutectics, which are further removed from conventional superalloys,[1] have higher strengths than the directional superalloy structures as a result of the high creep strength of the reinforcing phase. Wire-reinforced structures offer the greatest potential strength advantage. This strength advantage would be diminished somewhat if these data were density corrected. Whether the high density-corrected strengths of the wire-reinforced superalloys can be translated into useful turbine blade design strengths is yet to be demonstrated. The same concern expressed previously for strength at root attachment temperatures also applies to wire-reinforced superalloys.

Creep strength is directly related to ductility, since turbine blades are designed to a specific amount of allowable creep or blade extension. This allowable creep limit is based on the material's ability to deform prior to failure and must include a sufficient safety factor. A more ductile material is allowed to creep a greater amount, and, for a given lifetime, has a higher stress capability to reach the allowable design creep limit. Since the permissible creep limits usually are of the order of 1%, which is in the early stages of steady-state creep, improvements of approximately 200% in life and 15% in stress can be achieved by increasing the allowable creep limit to 2%.

Off-axis or transverse properties can be another limiting criterion. Although complex air-cooled blades have a higher ratio of transverse to longitudinal stresses than solid uncooled blades, the transverse ductility, and not the transverse strength, usually is the limiting criteria (Table 1). Alloying additions are made to directionally solidified columnar-grained superalloys to insure adequate transverse (perpendicular to grain boundaries) ductility. Single crystals are

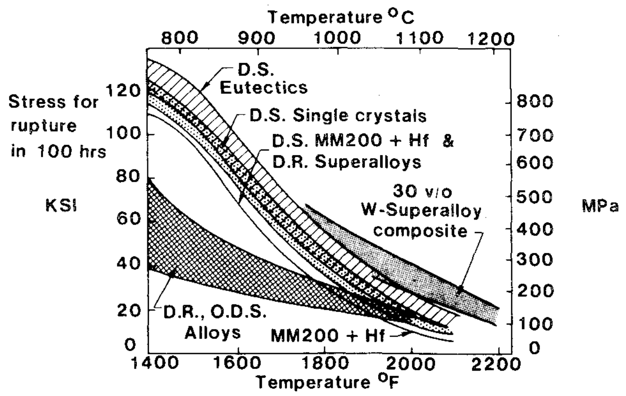

Fig. 9 Stress rupture properties of directional structures.

not ductility limited in the transverse blade directions, but their creep strength is a function of crystallographic orientation. Because turbine blades are not loaded uniaxially, the complex deformation occurring in turbine blades minimizes the effect of orientation on the creep properties of single-crystal superalloys.

Eutectics may exhibit limited ductility normal to their growth direction, and attention must be paid to this limitation when designing with the lamellar eutectics that have exhibited limited transverse creep ductility. Based on the limited data available on the transverse properties of directionally recrystallized conventional superalloys, no problems have been observed. We are unaware of any transverse property data on the oxide dispersion strengthened alloys. Wire-reinforced superalloys should exhibit much lower transverse properties than longitudinal properties, but should possess adequate transverse ductility, similar to that found with fibrous eutectic structures.

Thermal Fatigue Resistance

Improved thermal fatigue resistance can result in greater blade and engine durability and improved performance and fuel consumption because of its ability to use less cooling air with existing cooling schemes, or to operate at higher temperatures with the same amount of cooling air, or to employ more effective air cooling schemes, which place increased thermal fatigue demands on the turbine blade material.

A comparison of thermal fatigue resistance for directional turbine blade structures is given in Table 2. The alignment of the low modulus [100] orientation parallel to the blade, or growth axis in columnar-grained and single-crystal superalloys made by directional solidification, provides these materials with their superior thermal fatigue resistance.[18,19] Low modulus is an advantage in improving thermal fatigue resistance, since the strains in the blade are thermally induced, and a low modulus results in lower blade stresses. In addition, the yield strength of these DS superalloys is similar to that of conventionally cast superalloys, so that a greater portion of the thermally induced strain is elastic with these low modulus directional structures. Eutectics, depending upon the particular eutectic alloy, may have a low modulus, and therefore improved thermal fatigue resistance. The preferred orientation of more complex directionally recrystallized superalloys usually is [110], which is not a low modulus orientation; therefore, one would not expect significant improvements in their thermal fatigue resistance.[10] At the present time no data have been reported on the thermal fatigue resistance of these materials. Little data are available for wire-reinforced superalloys, but, in addition to the external strains, wire-reinforced superalloys also may be subjected to self-imposed fatigue damage as a result of the large thermal expansion mismatch between the reinforcing wire and matrix.[20] Although limited data suggest that this damage may not be too severe in tungsten-reinforced FeCrAlY,[16] microcracking has been observed in nickel alloy matrix composites;[21] additional testing is required to answer this question. Although very limited data are available for off-axis or transverse thermal fatigue resistance for any of the directional structures, this property should vary with transverse modulus, and as creep or rupture ductility, which was discussed previously.

Oxidation/Hot Corrosion Resistance

Aircraft gas turbine life (durability), directly, and fuel consumption and performance, indirectly, are influenced by turbine blade oxidation/hot corrosion resistance. Although almost all advanced turbine blade airfoils are coated for enhanced oxidation/hot corrosion resistance, there is an effect of substrate alloy on coated alloy properties; the turbine blade root usually is not coated.[22] Therefore, the oxidation/hot corrosion properties of directional turbine blade alloys are of great importance. This is especially true when a directional alloy has very poor oxidation/hot corrosion resistance compared to existing superalloys and may require a special coating. Although primarily applied for oxidation/hot corrosion protection, coatings can affect both creep and thermal fatigue resistance.[19]

Table 3 compares the oxidation/hot corrosion resistance of directional structures. Directionally solidified and recrystallized superalloys have oxidation/hot corrosion resistance equivalent to conventional superalloys, since these properties are insensitive to structure being primarily dependent on alloy composition. However, oxide dispersion strengthened directionally recrystallized alloys exhibit superior oxidation and hot corrosion resistance because of the beneficial effect of the finely dispersed oxide particles.[23] Single crystals, because of the added compositional freedom available from the elimination of the grain boundary strengthening elements, should have improved oxidation/hot corrosion resistance. Eutectics, depending on the particular eutectic, have been found with properties ranging from exceptionally good to very poor oxidation/hot corrosion resistance.[7] By selection of a sufficiently corrosion-resistant matrix, which surrounds each wire with sufficient thickness, a wire-reinforced superalloy should exhibit good oxidation/hot corrosion resistance. Serious attack, however, might result if

Table 1 Comparison of minimum-creep rupture ductility

Material	Longitudinal ductility	Off-axis ductility
Conventionally cast superalloy	3-5%	. . .
DS columnar grained superalloys	>5%	>2%
DS single crystal superalloys	>5%	>5%
DS eutectics	>5%	>1%
DR-superalloys	>5%	>2%
DR-ODS superalloys	~2-3%	no data
Wire-reinforced superalloys	>5%	no data

Table 2 Thermal fatigue properties

Structure	Room temperature modulus[a] (10^6 psi)	(GPa)	Relative thermal fatigue resistance
Conventionally cast superalloy	32	220	1
DS columnar-grained superalloy	19	131	10
DS single-crystal superalloy	18	124	10
DS eutectic[b]	34-19	234-131	<1 – 10
Directionally recrystallized superalloys and oxide dispersion strengthened alloy	32	220	1
30 v/o tungsten-wire-reinforced superalloy[b]	37	255	<1

[a]Thermal fatigue stresses depend on the product $E\alpha\Delta T$ (modulus, thermal expansion coefficient and temperature over which material is cycled).
[b]Differences in thermal expansion characteristics of constituent aligned phases may also be a source of thermal fatigue damage.

wires become exposed during service. Additional work is required to prove the reliability of the composite system in the corrosion enviornment of a high-temperature gas stream.

Other Material Properties

For some directional structures, other properties of secondary importance in the application of superalloys became increasingly critical. The increased density of the wire-reinforced superalloys is such a property. By selective reinforcement, and by reduction in blade airfoil thickness, it has been argued[24] that blades equal in weight to superalloys might be produced. Should this prove not to be feasible, significant increases in blade weights would result. This in turn, would place increased demands on the turbine disks.

For the wire-reinforced superalloys, wire-matrix reactivity at very high temperatures ≥2100°F (1150°C) presents another problem. With this interaction, wire strengths are degraded, and the composite creep-rupture properties therefore are diminished. Selection of nonreactive matrix alloys and the use of diffusion barriers have proven effective in minimizing this problem.[15]

Shear properties, required for current fir tree turbine blade attachment schemes, can be another problem area for directional structures. Some eutectic alloys have been found to have low shear strengths. Shear strength data on wire-reinforced or directional recrystallized alloys are not available.

Current Status of Advanced Directional Turbine Blade Materials

DS columnar-grained superalloys have received extensive laboratory evaluation and engine testing. They are currently bill-of-material in several advanced commercial and military aircraft gas turbine engines. DS single-crystal superalloys have been engine tested, but are behind columnar-grained superalloys in the development path with additional laboratory and engine testing programs planned for the next few years. Several DS eutectics have received extensive laboratory evaluation, and early engine testing is anticipated.

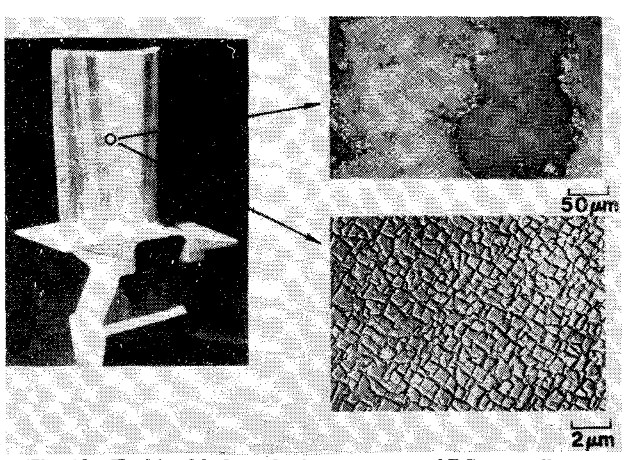

Fig. 10 Turbine blade and microstructure of DS superalloy.

Table 3 Coated oxidation and hot corrosion resistance

Structure	Properties
DS columnar-grained superalloys	Similar to conventionally cast superalloys
DS single-crystal superalloys	Anticipated improvement over conventional cast superalloys
DS eutectics	Properties highly dependent on system: observed behaviors range from much poorer to superior performance relative to superalloys
Directionally recrystallized superalloys and oxide dispersion strengthened alloys	Range of properties dependent on alloy: expected properties vary from equivalent to superior performance relative to conventional superalloys
Wire-reinforced superalloys	No better than superalloys

Directionally recrystallized, oxide dispersion strengthened and conventional superalloys currently are receiving extensive laboratory evaluation, with engine testing of vane alloys anticipated shortly, and engine testing of blade alloys planned in the next few years. Wire-reinforced superalloys have received the least attention recently of any of the directional turbine blade materials; advanced development work has yet to be undertaken, and engine testing is not anticipated in the near future.

Materials Assessment

Directionally cast columnar-grained superalloys are the baseline to which all other advanced turbine blade materials should be compared. A directionally cast turbine blade and microstructure of such a columnar-grained superalloy is shown in Fig. 10.

In the near term are directionally solidified single crystals and directionally recrystallized superalloys. DS single crystals are an extension of the columnar-grained DS technology, and offer further improvements in properties. A directionally cast single-crystal turbine blade and its microstructure are displayed in Fig. 11.

The modulus of directionally recrystallized alloys, suitable for use as turbine blades, is similar to that of conventionally cast superalloys and should afford no improvement in thermal fatigue resistance over that obtained with conventionally cast superalloys. Transverse properties have not proven to be a problem based on limited testing of conventional directionally recrystallized alloys, but may be of some concern with the less ductile oxide dispersion strengthened alloys. In addition, a suitable solution to the root attachment problem must be found for oxide dispersion strengthened directionally recrystallized alloys.

In the longer term, approximately ten years from initial incorporation as a turbine blade alloy, are the DS eutectics. DS eutectics require planar front growth with its associated restrictive solidification parameters to achieve the outstanding creep strengths that they have demonstrated. Despite these restrictions, both solid and air-cooled turbine blade shapes have been directionally cast from eutectics, as illustrated in Fig. 12. Transverse ductility, shear strength, thermal fatigue resistance, and oxidation/hot corrosion resistance all are

Table 4 Summary – advantages and challenges of directional structures

Structure	Advantages	Challenges
DS columnar-grained superalloys	Creep ductility and thermal fatigue resistance	Current production item, emphasis on cost reduction
DS single-crystal superalloys	Creep ductility, improved creep strength, and thermal fatigue resistance	Anisotropy
DS eutectics	Improved creep strength	Anisotropy, surface protection, and alloy processing
DR superalloys and ODS alloys	High-temperature creep strength	Anisotropy, processing ductility, and root attachment in the case of ODS alloys
Wire-reinforced superalloys	Outstanding creep strength	Anisotropy, thermal fatigue properties, processing, surface protection, and root attachment

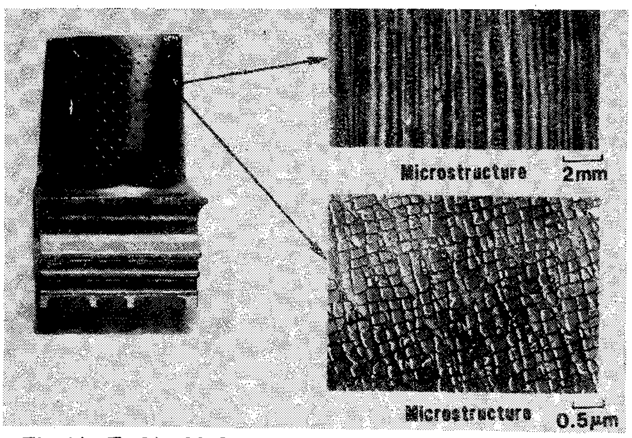

Fig. 11 Turbine blade and structure of DS single-crystal alloy.

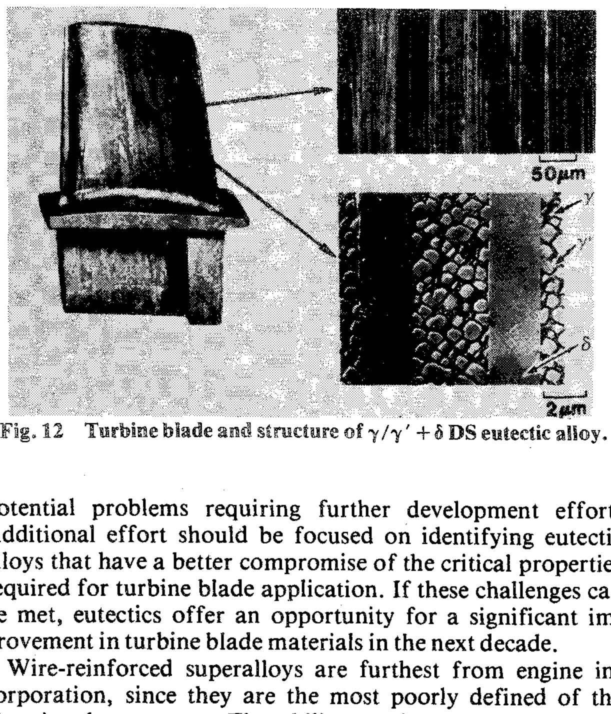

Fig. 12 Turbine blade and structure of $\gamma/\gamma' + \delta$ DS eutectic alloy.

potential problems requiring further development effort. Additional effort should be focused on identifying eutectic alloys that have a better compromise of the critical properties required for turbine blade application. If these challenges can be met, eutectics offer an opportunity for a significant improvement in turbine blade materials in the next decade.

Wire-reinforced superalloys are furthest from engine incorporation, since they are the most poorly defined of the directional structures. The ability to circumvent their high density by using graded wire layups to fabricate complex air-cooled turbine blades to use the outstanding high-temperature strength of these materials remains to be demonstrated. If achievable, blade fabrication will be an expensive process. Solid, prototype blades of uniform fiber density have been fabricated.[25] A solution to the root attachment problem also must be found for wire-reinforced superalloys. Additional data are needed on creep strength and ductility, thermal fatigue resistance, off-axis properties, matrix-wire interactions, and oxidation/hot corrosion resistance. In the absence of these data, it is difficult to make an assessment of wire-reinforced superalloys as an advanced turbine blade material.

Summary

The advantages and challenges of the directional turbine blade materials discussed in this paper are summarized in Table 4. Since each material candidate poses certain unanswered questions, continued research and development of all approaches appears justifiable. As answers are provided to these questions, emphasis can be given to the approach that seems most likely to perform to the potential it is said to offer.

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