DEVELOPMENT OF COATED SINGLE-CRYSTAL

SUPERALLOY SYSTEMS FOR GAS TURBINE APPLICATIONS

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Summary

Single-crystal (SC) alloy derivatives of the MAR-M 247 alloy were developed for turbine airfoil applications. This development activity focused on casting process technology, SC alloy microstructure/mechanical property relationships, and coating - SC alloy interactions.

Both the exothermic and withdrawal casting processes were evaluated for producing SC components and were found to produce equivalent material from a stress-rupture standpoint.

Microstructural effects associated with the removal of grain boundary strengthening elements (B, C, Zr, Hf), microporosity, recrystallized grains, and mu phase precipitation are reviewed from the standpoint of mechanical properties.

Coating-superalloy interactions were assessed from both mechanical and environmental standpoints. Thin coatings have not produced any reductions in SC alloy stress-rupture or high-cycle-fatigue properties. From an environmental standpoint, removal of the hafnium from the MAR-M 247 composition reduced the oxidation resistance of diffusion aluminide coatings. An overlay coating, SCC103, was consequently developed to provide significantly improved oxidation resistance and diffusional stability.

Introduction

Single-crystal (SC) superalloys represent the latest evolutionary advancement in cast turbine airfoil technology (Figure 1). In particular, superior mechanical properties of the SC alloys (Figure 2) make SC alloys attractive for turbine airfoil applications in advanced fuel-efficient, high-performance aircraft gas turbine engines. This paper reviews the development of SC components with emphasis on processing and effects of microstructure and protective coatings on mechanical properties and environmental resistance.

Mechanical Properties

Critical SC alloy mechanical properties (e.g., stress-rupture and fatigue strengths) are dependent upon a number of factors including composition, microstructure, processing, and coating effects. These aspects of SC technology are discussed in the following paragraphs.

Composition Considerations

Development of SC alloys at Garrett has focused predominantly on alloys derived from the MAR-M 247 alloy. Table I provides the compositions of MAR-M 247 and four of these derivative SC alloys that were extensively evaluated under NASA (1), Cannon-Muskegon (2), and Garrett-sponsored programs. Examination of this table indicates that the basic modification of MAR-M 247 was removal of virtually all the grain boundary strengthening elements (B, Zr, Hf, C), which are also melting point depressants. This change increased the incipient melting point from about 1240°C (2264°F) for MAR-M 247 up to 1330°C (2425°F) for NASAIR 100. Nearly complete solutioning of the γ' phase (Figure 3), followed by precipitation as fine particles, is primarily responsible for the improved creep-rupture strength of these SC alloys.

Other factors important to the development of the various SC alloy compositions are castability (Ta/W ratio), coated oxidation resistance (small Hf addition), and metallurgical stability (Co addition).

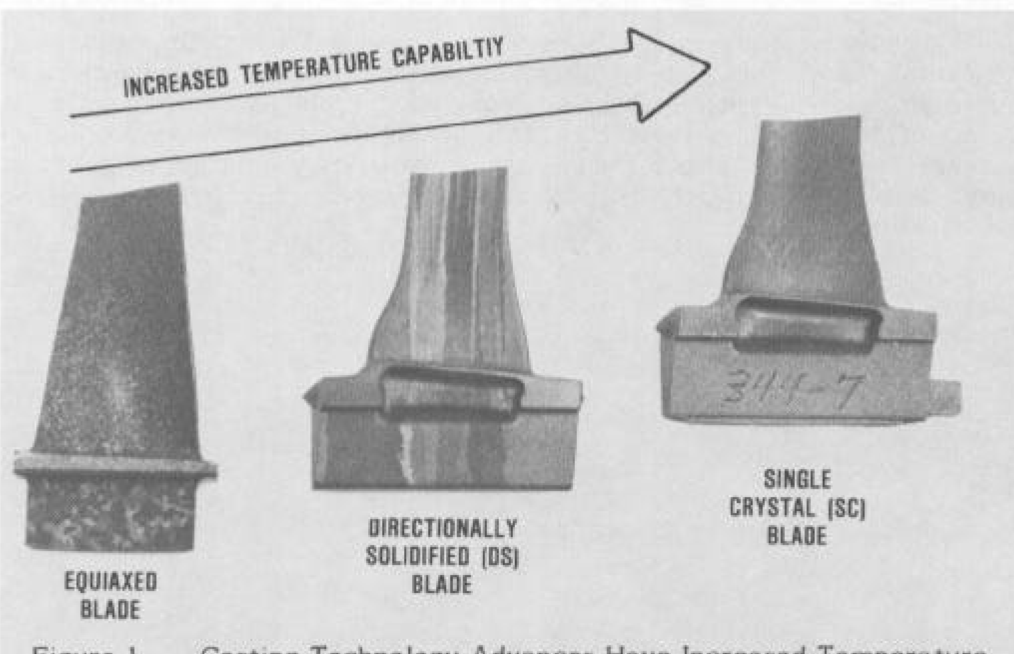


Figure 1. Casting Technology Advances Have Increased Temperature Capability of Turbine Airfoils.

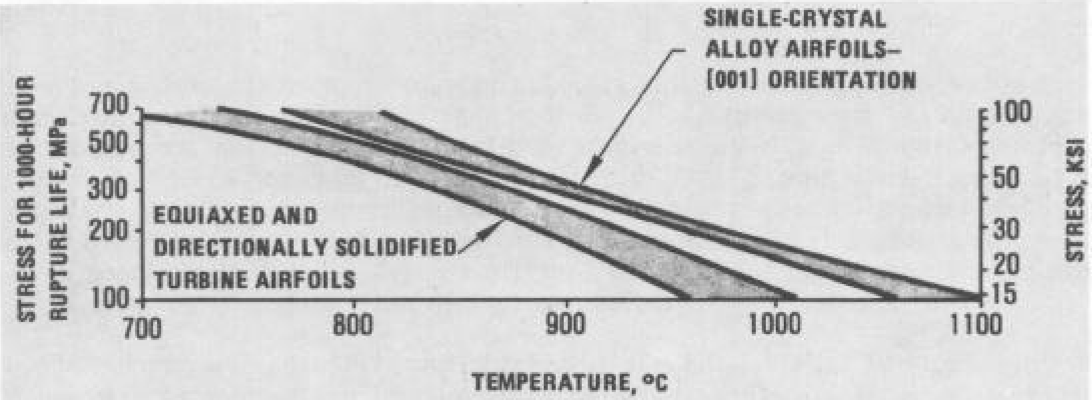
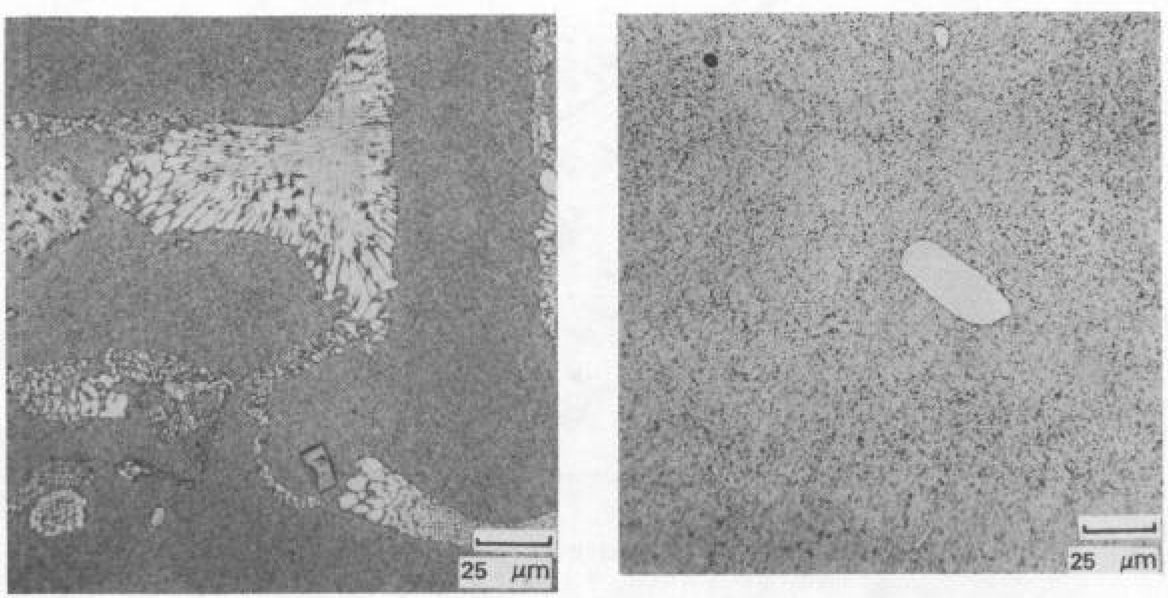


Figure 2. Single-Crystal Alloys Have Superior Temperature Capability for Advanced Turbine Airfoils.

Table I. Compositions of Single-Crystal Alloys Derived MAR-M 247 (Weight %).

Alloy	Mo	W	Ta	Al	Ti	Cr	Co	Hf	Zr	C	B	Ni
MAR-M 247	0.65	10.0	3.3	5.5	1.05	8.4	10.0	1.4	0.055	0.15	0.015	Bal
NASAIR 100	1.0	10.5	3.3	5.75	1.2	9.0	--	--	--	--	--	Bal
Alloy 3	0.8	9.5	3.3	5.65	1.05	8.5	5.0	0.25	--	--	--	Bal
CMSX-2	0.5	7.5	6.0	5.5	0.9	7.5	4.0	--	--	--	--	Bal
CMSX-3	0.5	7.5	6.0	5.5	0.9	7.5	4.0	0.1	--	--	--	Bal



MAR-M 247 (1246°C)/2 HRS

NASAIR 100 (1324°C)/4 HRS

Figure 3. SC NASAIR 100 Microstructure Is Almost Completely Homogenized During Solution Heat Treatment (in Contrast to MAR-M 247).

SC Microstructure

For the SC alloys listed in Table I, the rupture strength is predominantly a function of the γ' morphology (1,3). As indicated in Figure 4, rapid cooling from the solutioning temperature (e.g., 1.7 min to 816°C), followed by simulated coating (982°C/5 hours) and aging (871°C/20 hours) heat treatments, produces a finer gamma prime size associated with the superior stress-rupture properties. In contrast, the coarser γ' particle size, associated with slow cooling from the solutioning temperature (e.g., 4.4 minutes to 816°C) or a long-time exposure at high-temperature (e.g., 982°C/1000 hours), results in a significant reduction in the rupture strength.

One of the SC alloys, NASAIR 100, exhibited evidence of mu phase and alpha tungsten in the microstructure. However, this microstructural characteristic did not produce any degradation in the alloy's mechanical properties--stress rupture and high-cycle fatigue (HCF)--even after long-term, high-temperature exposure. Isothermal stress versus rupture life data for SC NASAIR 100 and SC Alloy 3 (which is metallurgically stable) are provided in Figure 5 to illustrate this conclusion. These data indicate that the rupture life curves at 871°, 982°, and 1093°C (1600°, 1800°, and 2000°F) have the same slopes for both alloys. Since mu phase precipitation in NASAIR 100 occurs after about 100 hours, it is apparent that the stress-rupture capability was essentially unaffected by the precipitation of the mu phase.

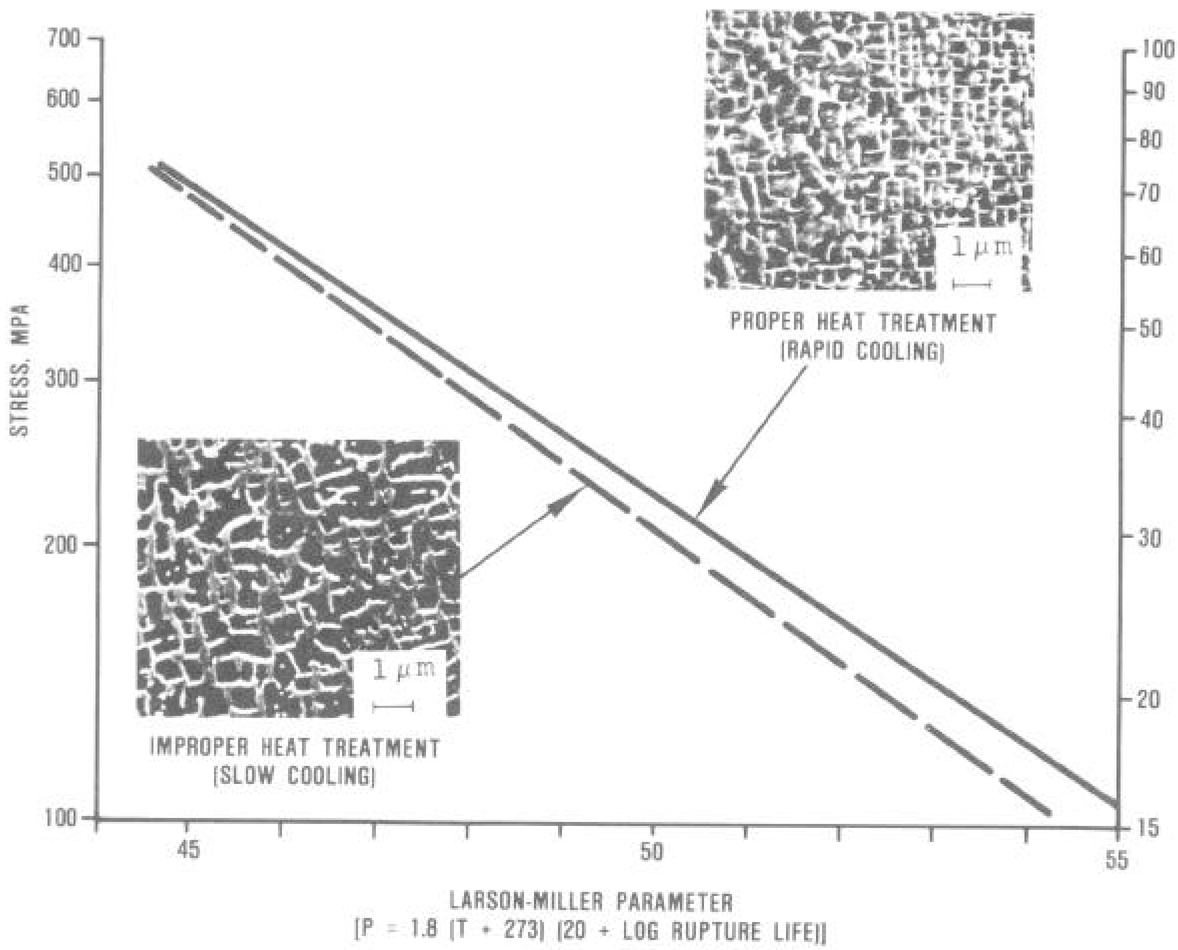


Figure 4. Microstructure and Stress-Rupture Life of SC NASAIR 100 Are Improved by Rapid Cooling from the Solutioning Temperature.

For SC alloys produced by commercial withdrawal and exothermic processes, microporosity has been the dominant imperfection associated with initiation of fatigue and stress-rupture cracking (1,2). Also, it has been reported that very low porosity SC CMSX-2, produced with a laboratory high gradient furnace, exhibited a significant increase in HCF strength (2).

In an effort to eliminate the microporosity associated with crack initiation, SC NASAIR 100 specimens were cast by the withdrawal process, hot isostatically pressed (1260°C/193 MPa/3 hours) and then fully heat-treated. However, no significant improvements in either stress-rupture or low-cycle fatigue were obtained. Subsequent examination of the specimens indicated that small recrystallized grains had formed in the material during hot isostatic pressing. These grains were of comparable size to the porosity that was eliminated (Figure 6). The localized deformation associated with pore closure was considered to be a contributing factor to the formation of the recrystallized secondary grains. As indicated in Figure 7, these small recrystallized grains are about as effective as porosity in initiating fatigue cracks.

Processing

The SC alloys listed in Table I have been cast by both exothermic and withdrawal casting processes. Both of these processes have been found capable of producing equivalent material for small turbine blades from a mechanical properties (e.g., stress-rupture and fatigue) standpoint. Of particular interest, stress-rupture data for SC NASAIR 100, CMSX-2, and CMSX-3 produced by both exothermic and withdrawal processes were observed to be effectively characterized by a single stress versus Larson-Miller parameter relationship.

Coatings

The influence of protective coatings on mechanical properties (creep rupture and HCF) has also been examined. In this investigation, thin (approximately 50 μm thickness) diffusion aluminide coatings were determined to have no significant effect on creep-rupture strength (Figure 5).

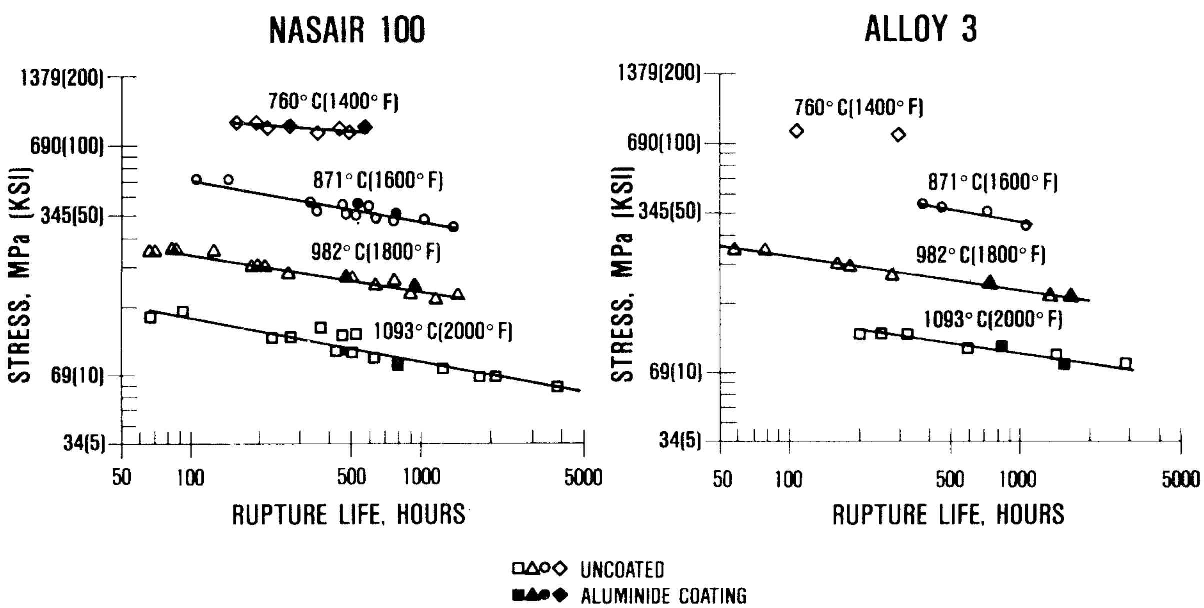


Figure 5. Diffusion Aluminide Coatings and Mu Phase Precipitation Do Not Significantly Affect SC Alloy Stress-Rupture Life.

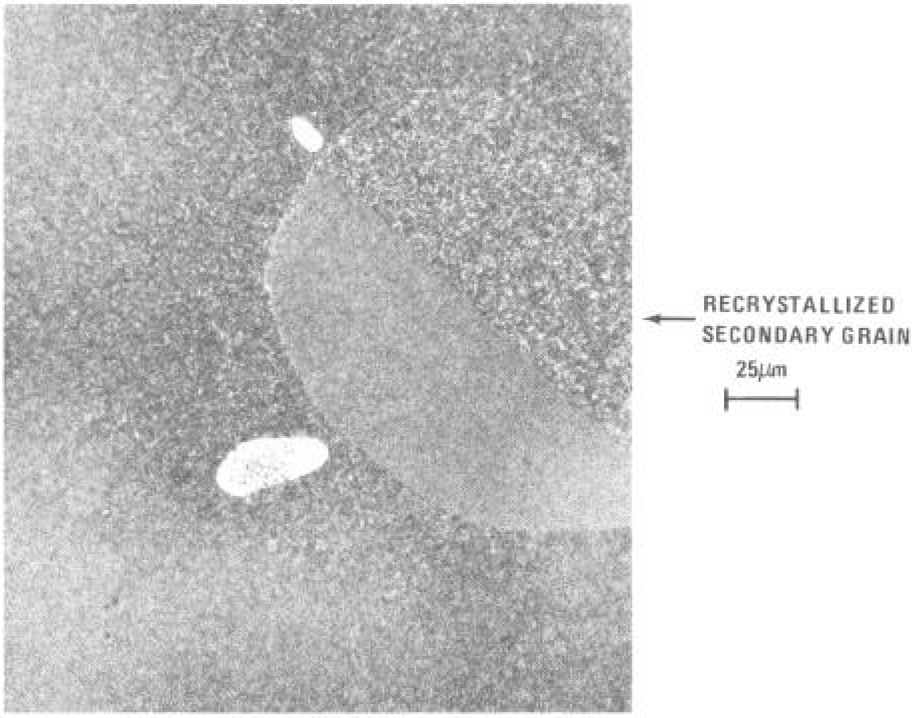


Figure 6. Recrystallized (Twinned) Secondary Grains Were Observed in SC NASAIR 100 After Hot Isostatic Pressing.

Effects of several potential coating process temperatures on the stress-rupture properties of the CMSX-3 single-crystal alloy were evaluated. Relative to material given the baseline heat-treatment (1302°C/3 hours + 982°C/5 hours + 871°C/20 hours), none of the simulated coating process temperature conditions examined provided any significant improvement in 982°C/248 MPa (1800°F/36 ksi) stress-rupture capability, which is critical from a turbine blade design standpoint. When a 1052°C/4 hour heat treatment was substituted for the 982°C/5 hour simulated coating process temperature, an improvement in higher stress/lower temperature stress-rupture life was observed, which is in agreement with results reported by Khan, et al (4). However, in contrast with the Khan study, no improvement was observed at lower stress/higher temperature conditions.

As indicated in Figure 8, the HCF strength of the SC alloys was not compromised by thin diffusion aluminide coatings. In the HCF testing, numerous cracks were observed in the diffusion aluminide coatings on both the SC NASAIR 100 and directionally solidified (DS) MAR-M 247 specimens. However, these cracks were not sufficiently severe, from a stress intensity factor standpoint, to reduce the 10^7 cycle uncoated strength of these superalloys.

This result is consistent with previous studies on other coated superalloy systems (5). In those studies, cracks in thin coatings were no more severe, from a substrate crack initiation standpoint, than defects (e.g., microporosity) present in the superalloy. In contrast, thicker coatings are capable of accelerating the initiation of HCF cracking in the superalloy substrate.

Environmental Properties

In most gas turbine applications, the SC alloys will require coatings to achieve the desired component lives. Consequently, the performance of protective coatings has been extensively investigated.

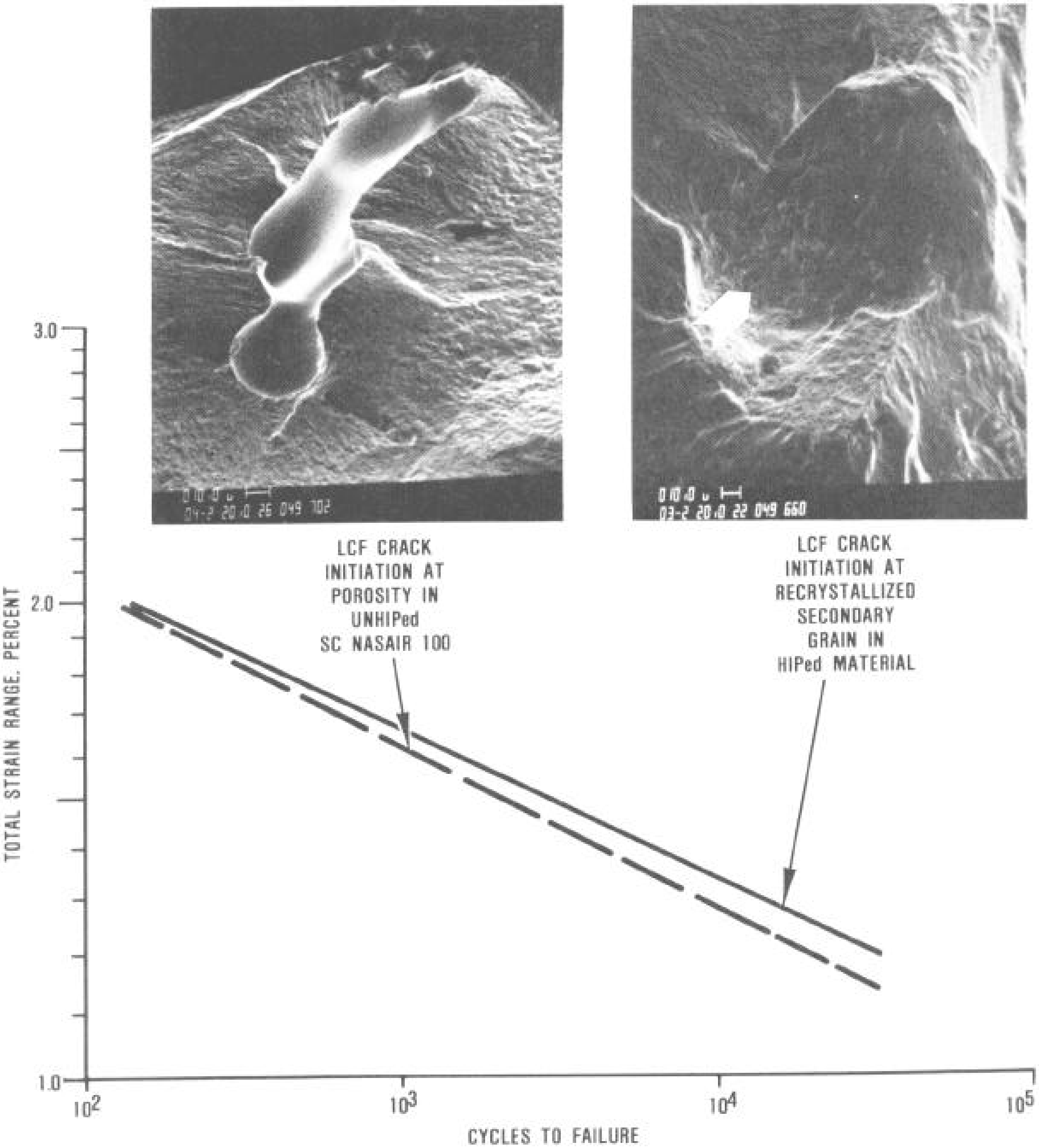


Figure 7. Porosity and Recrystallized Secondary Grains Are Initiation Sites for Fatigue Cracks in SC NASAIR 100 (649°C, A=∞, 0.33 Hertz).

Initial evaluations were focused on Chromalloy RT-21 diffusion aluminide coatings, which are widely used for protecting conventionally cast and DS superalloy (e.g., MAR-M 247) components in commercial engines. During cyclic burner rig oxidation testing, the oxidation resistance of the aluminide coatings was observed to be adversely affected by the SC alloys (Figure 9). The primary reason for this result is the removal of hafnium from the superalloy. In MAR-M 247 (1.4 percent Hf), the hafnium diffuses into the coating and enhances adhesion of the predominantly aluminum oxide scale, which inhibits additional oxidation. In contrast, when applied to

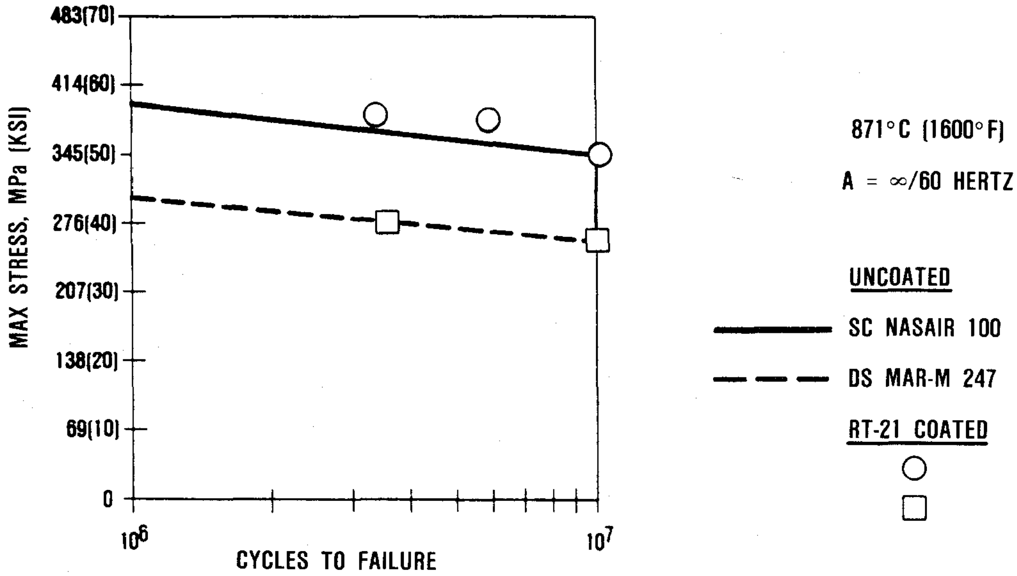


Figure 8. Thin (50μm Thick) Diffusion Aluminide Coatings Do Not Significantly Affect the HCF Capabilities of Single-Crystal and Directionally Solidified Superalloys.

SC alloys with no hafnium, such as NASAIR 100, diffusion aluminide coatings experience repeated spalling of the aluminum oxide scale during thermal cycling and, consequently, have shorter lives.

Two of the SC alloys, CMSX-3 and Alloy 3, have small additions of hafnium that are consistent with the solution heat treatment requirements. These hafnium additions (0.1 to 0.25 percent) to the alloy composition improve the oxidation resistance of diffusion aluminide coatings relative to SC NASAIR 100, but fall short of coating lives on MAR-M 247.

Since Garrett's applications for SC alloys are at significantly higher temperatures than MAR-M 247, an improved, low-pressure plasma-sprayed overlay coating system, SCC103, was developed. Particular attention was given to optimizing oxidation resistance while maintaining good diffusional stability with the SC substrate. Cyclic oxidation burner rig testing conducted at 1149°C (2100°F) for 500 hours verified that this objective was achieved.

Surface stability of the protective oxide scale on the coating's surface is also an important criterion from the standpoint of maximizing coating life. In particular, multi-temperature testing in a burner rig (or in an engine) can produce surface rippling in some coating systems. The rippling mode of degradation is associated with coating-superalloy thermal expansion mismatch stresses and cyclically reversed creep deformation in the coating. SCC103 has been tailored to inhibit this mode of coating degradation on SC alloys, relative to other oxidation-resistant coatings such as NiCrAlY.

Summary

Single-crystal alloys represent the latest advancement in cast turbine airfoil metallurgy. Optimized mechanical properties are predominantly a function of SC alloy composition and microstructural parameters. Environmental resistance has been optimized by developing the coating and the superalloy as a system.

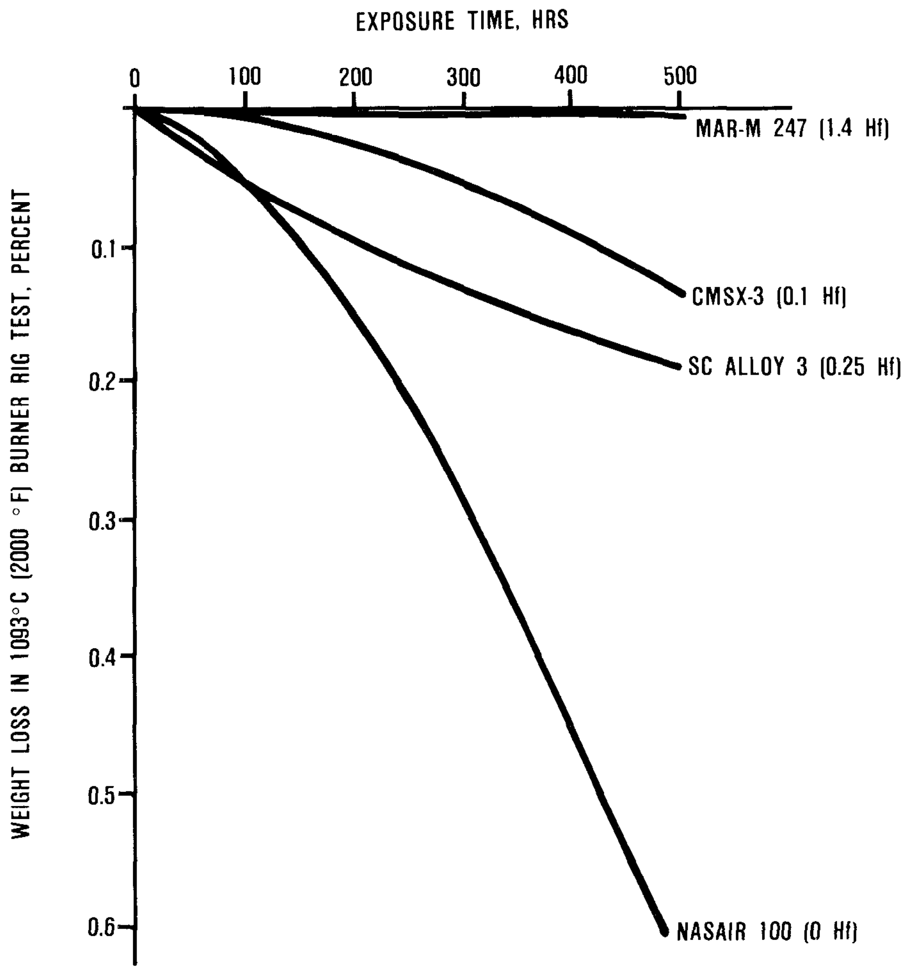


Figure 9. Oxidation Protection of Diffusion Aluminide Coatings Is Reduced in Single-Crystal Alloys.

Acknowledgment

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