NASA Technical Memorandum 79088

(NASA-TM-79088) AN OXIDE DISPERSION STRENGTHENED ALLOY FOR GAS TURBINE BLADES (NASA) 13 p HC A02/MF A01 CSCL 21H

N79-20180

Unclas
G3/20 17056

AN OXIDE DISPERSION STRENGTHENED ALLOY FOR GAS TURBINE BLADES

T. K. Glasgow
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER to be presented at the
Twentieth Structures, Structural Dynamics and Materials Conference
cosponsored by the American Institute of Mechanical Engineers,
and the American Society of Civil Engineers
St. Louis, Missouri, April 4-6, 1979

E-9912

AN OXIDE DISPERSION STRENGTHENED ALLOY FOR GAS TURBINE BLADES

T. K. Glasgov
National Aeronautics and Space Administration
Levis Research Center
Cleveland, Ohio

Abstract

The strength of the newly developed alloy MA-6000E is derived from a nickel alloy base, an elongated grain structure, naturally occurring precipitates of gamma prime, and an artificial distribution of extremely fine, stable oxide particles. Its composition is Ni-15Cr-2Mo-2Ta-4W-4.5Al-2.5Ti-0.15Zr-0.05C-0.01B-1.1Y_2O_3. It exhibits the strength of a conventional nickel-base alloy at 1400° F but is quite superior at 2000° F. Its shear strength is relatively low, necessitating consideration of special joining procedures. Its high cycle, low cycle, and thermal fatigue properties are excellent. The relationship between alloy microstructure and properties is discussed.

Introduction

Recently, a promising new alloy, MA-6000E, for potential use as a gas-turbine blade was developed by H. F. Merrick, L. R. Curwick, and Y. G. Kim of the International Nickel Co.[1,2]. The alloy, identified under a contract from the Lewis Research Center of NASA, derives its strength from a combination of mechanisms rarely found in a single alloy. These include solid solution hardening, the presence of the precipitated phase γ', and a highly elongated grain structure common to cast alloys, and oxide dispersion strengthening (ODS), a strengthening mechanism not found in conventional alloys. At 2000° F MA-6000E can sustain for long times twice the load of a conventional cast alloy. Its superior high temperature properties have already attracted the interest of several gas-turbine engine manufacturers. Because its strength varies with direction, MA-6000E presents designers of engines with both unusual opportunities and unusual problems. MA-6000E is produced via a special powder metallurgy process called "mechanical alloying". Described below are the special attributes of MA-6000E, the mechanisms from which it derives its strength, the mechanical alloying process, results of recent fatigue and shear tests, and finally some of the problems and potentials of application of MA-6000E as a gas turbine blade.

General Characteristics of MA-6000E

Table I lists the composition and some of the characteristics of MA-6000E. The composition was selected to have a balance of strength, oxidation, and corrosion resistance not found in previous ODS alloys. The density at 8.1 g/cm^3 is below that of the most commonly used cast blade alloys B-1900 (8.2 g/cm^3) and Mar-M200 (8.53 g/cm^3). The incipient melting temperature at 2365° F is comfortably high, falling between that of B-1900 (2325° F) and of Mar-M200 (2400° F). Tensile data show that the elevated temperature transverse tensile strength and ductility are somewhat below those determined in the longitudinal direction. Such anisotropy of properties is characteristic of ODS and other materials with elongated microstructure. Samples showing the elongated microstructure that may be developed in either extruded or hot-rolled MA-6000E are shown in Fig. 1. To observe both the γ' precipitates and the oxide dispersion, transmission electron microscopy must be used; in Fig. 2, from the work of R. K. Hotzler at NASA-Lewis Research Center, the cuboidal precipitates are γ' and the smaller round particles are yttrium/aluminum oxide dispersoids. Hard particles larger than 1 micron do not survive the mechanical alloying process and are not found in the final product. This contrasts sharply with conventional powder metallurgy products in which foreign particles (inclusions) as large as 40 μm in diameter may sometimes be found.

Mechanical Alloying

The special process (Fig. 3) by which the four strengthening mechanisms of solid solution, γ', oxide dispersion, and elongated grain structure are combined was invented by J. S. Benjamin of the International Nickel Co.[3]. A part of this process is mechanical alloying in which metal powders, atomized, crushed, or precipitated, are blended and kneaded together with fine oxide particles in a high energy, stirred ball mill. Mechanical alloying is performed dry in a controlled atmosphere provided, for example, by sealing air in the mill at the start of a run[3]. Repeated welding and fracture take place; this process results in a powder product containing all added elements and the oxides uniformly distributed throughout each particle. During the welding and fracturing, any undesirably large particles are broken down to smaller size. Among many powder processing methods tried, this one has been uniquely capable of handling the highly reactive aluminum and titanium necessary for both γ' formation and oxidation resistance without introducing excesive contamination. The process itself is interesting because it is amenable to the production of widely different alloys that cannot be made by conventional maens, primarily because the components being mixed need not be soluble in one another in either the liquid or solid states. For example a copper alloy containing fine precipitates of iron in much greater quantities than could be included by conventional casting can be prepared by this method[4].

Mechanically alloyed powder is typically consolidated by extrusion which, in the case of MA-6000E, is followed by hot rolling. Then, gradient annealing creates the elongated grain structure. Finally, the alloy is heat treated to bring out the full potential of the γ' phase.

Rupture Properties

The 1000-hour rupture strength capability of MA-6000E at 1400° to 2000° F is displayed in Fig. 4. Data[5] are included for a simple (γ'-free) oxide dispersion strengthened alloy, TD-Ni, and directionally solidified (DS) Mar-M200 + Hf, the most capable cast gas-turbine alloy in commercial service. DS Mar-M200 + Hf is strengthened by solid solution, by more than 50 volume percent γ', and by an elongated grain structure. MA-6000E is strengthened by the above three mechanisms plus oxide dispersion strengthening. TD-Ni derives its strength from oxides and grain structure. The high temperature superiority of MA-6000E is evident, and it is this increase in temperature capability that has interested several engine manufacturers.

The 1400° F strength level shown by TD-Ni is not sufficient for the higher stressed root and airfoil base portions of a gas-turbine blade. The strength of MA-6000E at 1400° F is almost equal to that of a currently employed conventionally cast turbine blade alloy, B-1900. The drastic improvement over TD-Ni at 1400° F may be attributed primarily to the successful addition of γ' strenghening. A summary plot of MA-6000E rupture properties (Fig. 5) shows a characteristic of ODS alloys. The slope of the stress versus life plot is very gradual. This can be important for rupture-life-limited components such as gas-turbine blades. A slight decrease in design stress can result in greatly extended part life. The more rapid dropoff in strength of Mar-M200 at 1600° F is characteristic of conventional superalloys.

ORIGINAL PAGE IS OF POOR QUALITY

Fatigue

The high cycle fatigue strength of MA-6000E has been determined using R. R. Moore-type rotating beam specimens[2]. Tests were performed in air at room temperature, at 1400° and at 1800° F. The high cycle fatigue data for MA-6000E are plotted along with comparable data for Udimet 700, an older blade superalloy[6] in Fig. 6. No comparable data were located for the more advanced conventional alloys B-1900 and Mar-M200. Fully reversed axial loading was performed to determine low cycle fatigue behavior. Diametral strain controlled tests[2] were conducted at room temperature and at 1400° F. The number of cycles to failure at 1400° F is presented as a function of the total strain range in Fig. 7. Room temperature data for MA-6000E fall along the same line as the 1400° F data. Figure 7 also includes data at 1400° F for conventionally cast and directionally solidified Mar-M200.

It is evident that the oxide dispersion strengthened alloy MA-6000E enjoys a considerable fatigue advantage over conventional alloys. In a direct comparison[7] of a much simpler ODS alloy, MA-753, and its wrought conventional counterpart, Nimonic 80, the ODS alloy also showed distinct superiority from room temperature to the highest temperature of test, 1750° F, indicating that fatigue superiority may be generic to ODS alloys. The favorable orientation of grain boundaries perpendicular to the crack propagation direction must be credited with some of this improvement, especially at elevated temperatures. But two other factors also play a part. First, the uniform dispersion of fine oxide particles in MA-6000E or any other ODS alloy greatly discourages the concentration of deformation into definite slip bands and thus discourages local cleavage cracking. And second, the absence of oxides, carbides, or other hard phases in sizes larger than 1 micron avoids the premature crack initiation at large hard particles observed in conventional powder metallurgy alloys in high cycle fatigue. The above results show that a large volume fraction of hard particles, approximately 3 vol% in the case of MA-6000E, can readily be tolerated in a superalloy if the particles are fine and well dispersed. This suggests that an alternative to the expensive removal of tramp hard particles from conventional superalloy powders may be to mechanically reduce their size.

Thermal Fatigue

While comparative data were difficult to find for high and low cycle fatigue, a large number of alloys have been evaluated in thermal fatigue in an on-going NASA project[8]. The thermal fatigue tests use a double wedge specimen (Fig. 8), which is cycled from a hot fluidized bed to a cooler bed. Samples are rated in thermal fatigue resistance by the number of cycles to the first visible crack. Past results have shown that thermal fatigue resistance improves generally with increasing high temperature strength, with increasing ductility, and with orientation of grain boundaries perpendicular to the crack propagation direction as in the case of directionally solidified (DS) alloys tested in the longitudinal direction. The addition of an oxidation resistant overlay coating, such as NiCrAlY, also improves fatigue life. Though test life is not yet complete, it has been noted (Fig. 8) that MA-6000E already ranks with the best of alloys.

Shear Strength

Determination of the short time shear properties has shown that ODS alloys as a class, suffer from relatively low shear strength[9]. Because the grain boundaries of an ODS alloy lie parallel to the shear direction in longitudinal tests, this was not unexpected. Creep shear tests of MA-6000E have just begun at NASA Lewis. These tests are being performed on simulated fir tree specimens, so the stress state will resemble that in a real turbine blade root application. In Fig. 9 the comparison between shear strength of the directionally solidified eutectic γ/γ'-δ[10] and MA-6000E is shown. Both these alloys were tested as simulated blade roots. The data for B-1900 was determined in pure shear. Based on only three tests, the 100-hour, 1400° F shear rupture strength of MA-6000E is about 34 ksi. While this is considerably better than γ/γ'-δ, it is well below the capability of a conventional cast superalloy, like B-1900.

Because the shear strength of MA-6000E is low, consideration must be given to modified root design or special means of holding an ODS airfoil in a turbine disk. It has been suggested that a conventional alloy root portion could be bonded to an ODS alloy airfoil. If, however, there is substantial diffusion across the bond joint during the bonding cycle, porosity such as that observed in oxidation testing may be expected. Alternatively, it may be possible to alter the typical parallel grained structure of the ODS alloy in the attachament region. Preliminary tests at NASA Lewis[11] have shown that the grains can be induced to grow laterally during recrystallization under the influence of a steep thermal gradient.

Conclusion

An unusually capable alloy, MA-6000E, has been identified, which combines strengthening from solid solution, from precipitates of γ', from an oxide dispersion, and from an elongated grain structure. Its balance of properties makes it very attractive for use as a gas-turbine blade. MA-6000E exhibits excellent fatigue properties which are not only interesting in their own right, but also indicate a possible way to improve the fatigue properties of conventional powder metallurgy alloys. The potential gains of substituting an ODS alloy such as

MA-6000E for a conventional alloy have been calculated by J. S. Benjamin[12]. They include increases in turbine inlet temperature of up to 400° F and increases in the static thr ' capacity of up to 25%. Before these benefits may be realized, problems in providing oxidation protection and in attaching ODS airfoils to turbine disks must be solved.

References

1. Merrick, H. F., Curwick, L. R., and Kim, Y. G.: "Development of an Oxide Dispersion Strengthened Turbine Blade Alloy by Mechanical Alloying," NASA CR-135150, Jan. 1977.
2. Kim, Y. G. and Merrick, H. F., "Characterization of an Oxide Dispersion Strengthened Superalloy, MA-6000E, for Turbine Blade Applications," NASA CR-159493, 1979.
3. Benjamin, J. S., "Dispersion Strengthened Superalloys by Mechanical Alloying," Metallurgical Transactions, Vol. 1, No. 10, 1970, pp. 2943-2951.
4. Benjamin, J. S., "Mechanical Alloying," Scientific American, Vol. 234, No. 5, May 1976, pp. 40-48.
5. High Temperature, High Strength Nickel Base Alloys, The International Nickel Company, Inc., New York, 3rd ed., July 1977.
6. Nakamura, Y., "Some Metallographic Observations on the 1500° F (815° C) Fatigue Fracture Surface of Wrought Udimet 700," Metallurgical Transactions, Vol. 5, No. 12, Dec. 1974, pp. 2605-2607.
7. Weber, J. H. and Bomford, M. J., "High-Cycle Fatigue Properties of a Dispersion Strengthened Nickel-Base Superalloy," in Fatigue at Elevated Temperatures, ASTM STP-520, A. E. Carden, ed., American Society for Testing and Materials, 1973, pp. 427-437.
8. Bizon, P. T. and Spera, D. A., "Comparative Thermal Fatigue Resistances of Twenty-Six Nickel- and Cobalt-Base Alloys," NASA TN D-8071, 1975.
9. Glasgow, T. K., "Longitudinal Shear Behavior of Several Oxide Dispersion Strengthened Alloys," NASA TM-78973, 1978.
10. Sheffler, K. D. and Jackson, J. J., "Stress Analysis, Thermomechanical Fatigue Evaluation, and Root Subcomponent Testing of Gamma/Gamma Prime-Delta Eutectic Alloy," NASA CR-135005, Dec. 1976.
11. Hotzler, R. K. and Glasgow, T. K., "Recrystallization Characteristics of an Oxide Dispersion Strengthened Superalloy, MA-6000E," NASA TM to be published.
12. Benjamin, J. S., "The Potential of Oxide Disperson Strengthened Superalloys for Advanced Gas Turbines," ASME Paper 76-GT-118, Mar. 1976.

TABLE I. - CHARACTERISTICS OF MA-6000E

Composition, wt%: 15Cr, 2Mo, 4W, 4.5Al, 2.5Ti, 2Ta, 0.05C, 0.01B, 0.15Zr, 1.1Y_2O_3, Balance Ni:.

Density: 8.1 g/cm^3
Incipient melting temperature: 2365° F
Oxidation/corrosion resistance: requires coating as do other Ni-base alloys
Gamma prime solvus: 2135° F
Gamma prime fraction: 50 vol%
Dispersed oxide fraction: 2 vol%
Structure: large elongated grains

TENSILE TEST DATA

Temperature	Yield strength, ksi	Ultimate tensile strength, ksi	% Elongation	% RA
Parallel to working direction				
RT	186	188	3.5	3.0
1400° F	113	142	5.5	12.5
2000° F	28	32	9.0	31.0
Transverse to rolling direction				
RT	179	185	5.5	3.0
1400° F	117	130	3.5	2.5
2000° F	25	26	2.0	1.0

(a) Extruded Bar.

(b) Extruded Plus Hot Rolled Plate.

Figure 1. - Macrostructure of extruded, and extruded plus hot rolled MA6000E after recrystallization by gradient annealing.

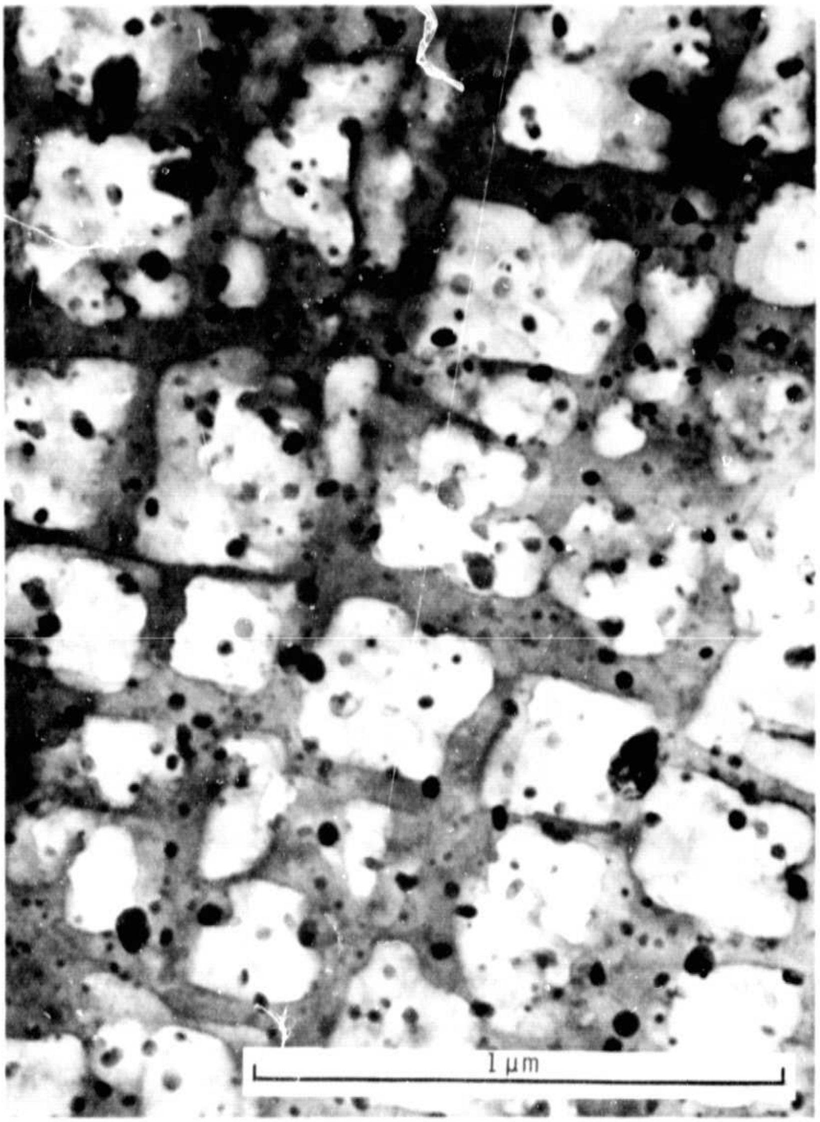

Figure 2. - Fully heat treated MA-6000E observed by tranmission electron microscopy. Gamma prime precipitates appear cubic; smaller round particles are oxide dispersoids.

E-2712

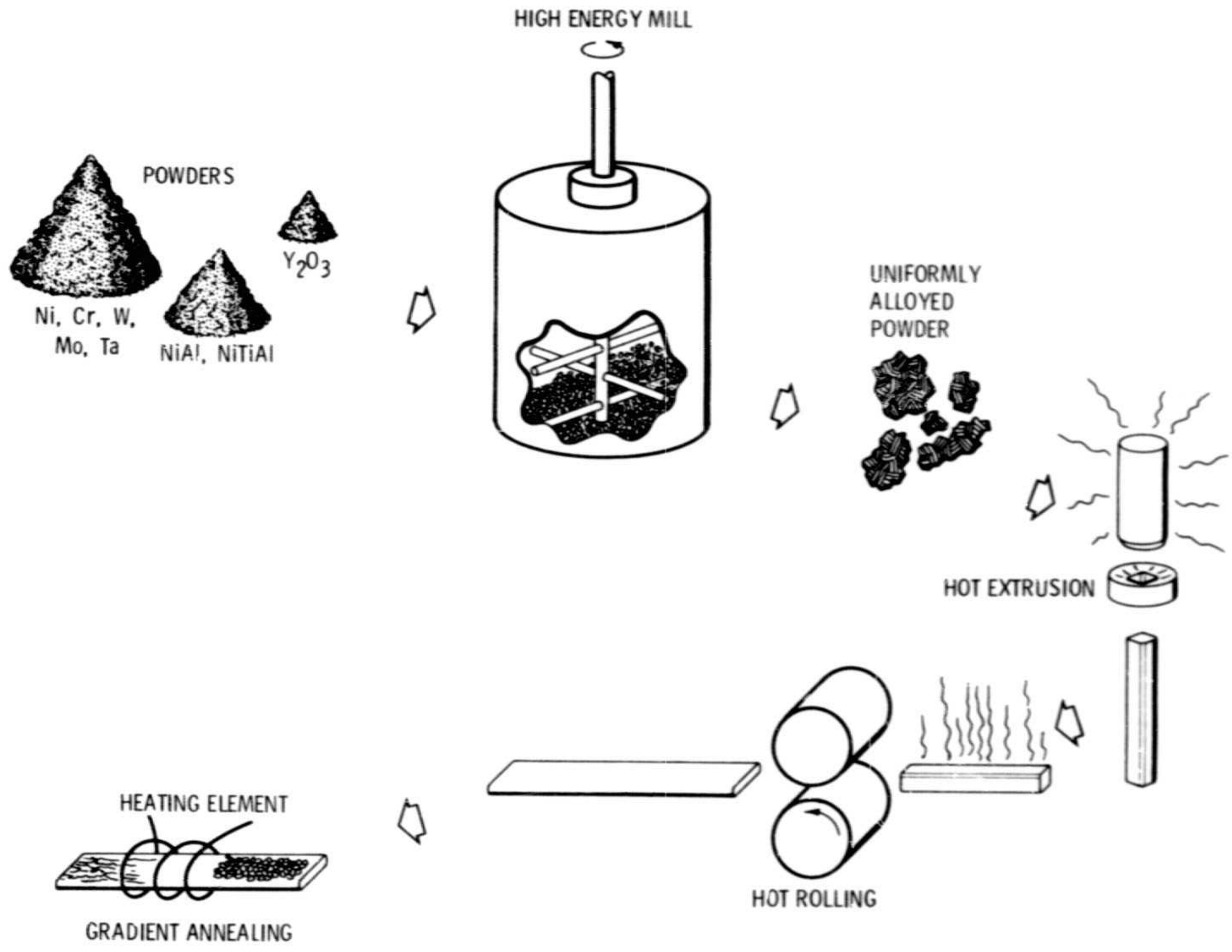

Figure 3. - Process for manufacture of an oxide dispersion strengthened superalloy.

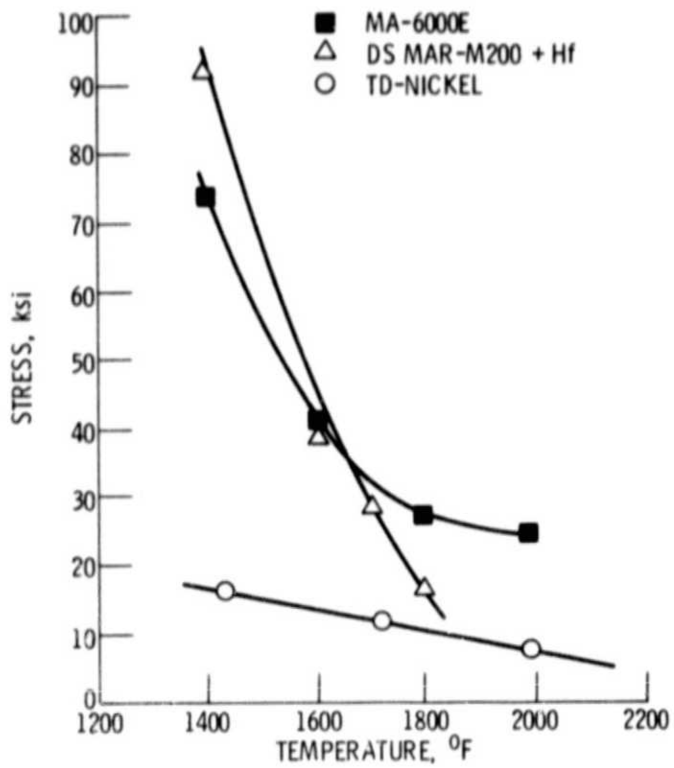

Figure 4. - Comparison of 1000 hour rupture strength capability of MA-6000E with DS Mar-M200 + Hf and with TD-nickel.

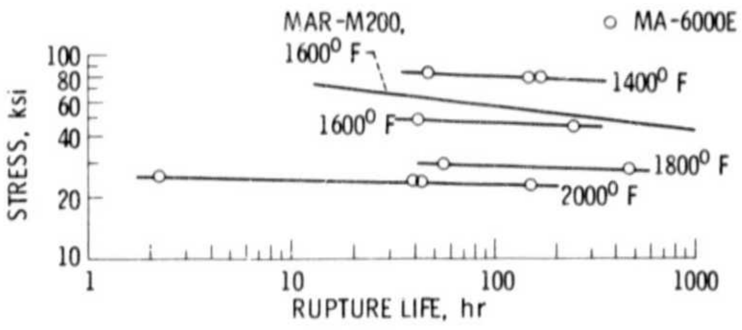

Figure 5. - Rupture life of MA-6000E and of a conventional nickel base superalloy.

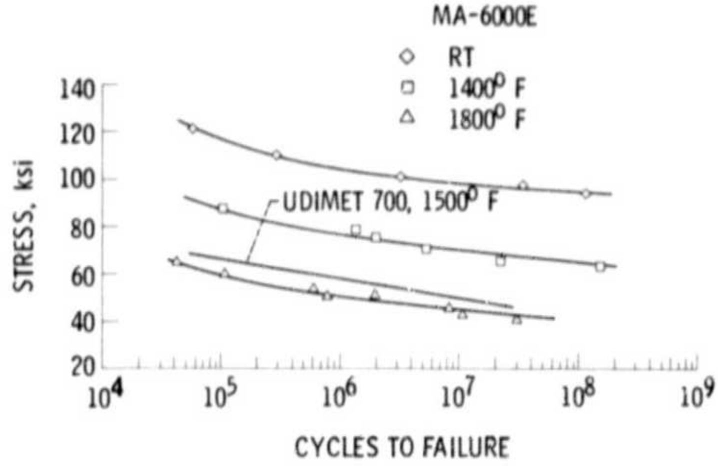

Figure 6. - Rotating beam high cycle fatigue behavior of MA-6000E.

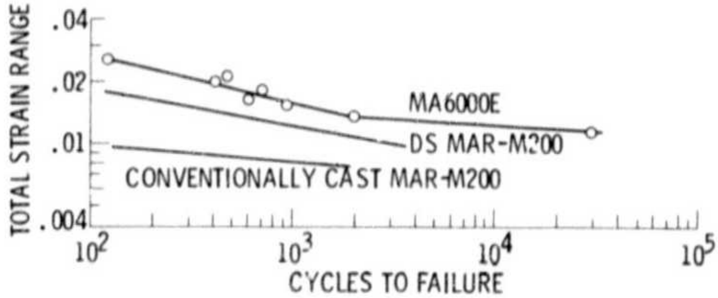

Figure 7. - Low cycle strain controlled fully reversed fatigue behavior of MA-6000E at 1400° F compared with directionally solidified and conventionally cast MAR-M200.

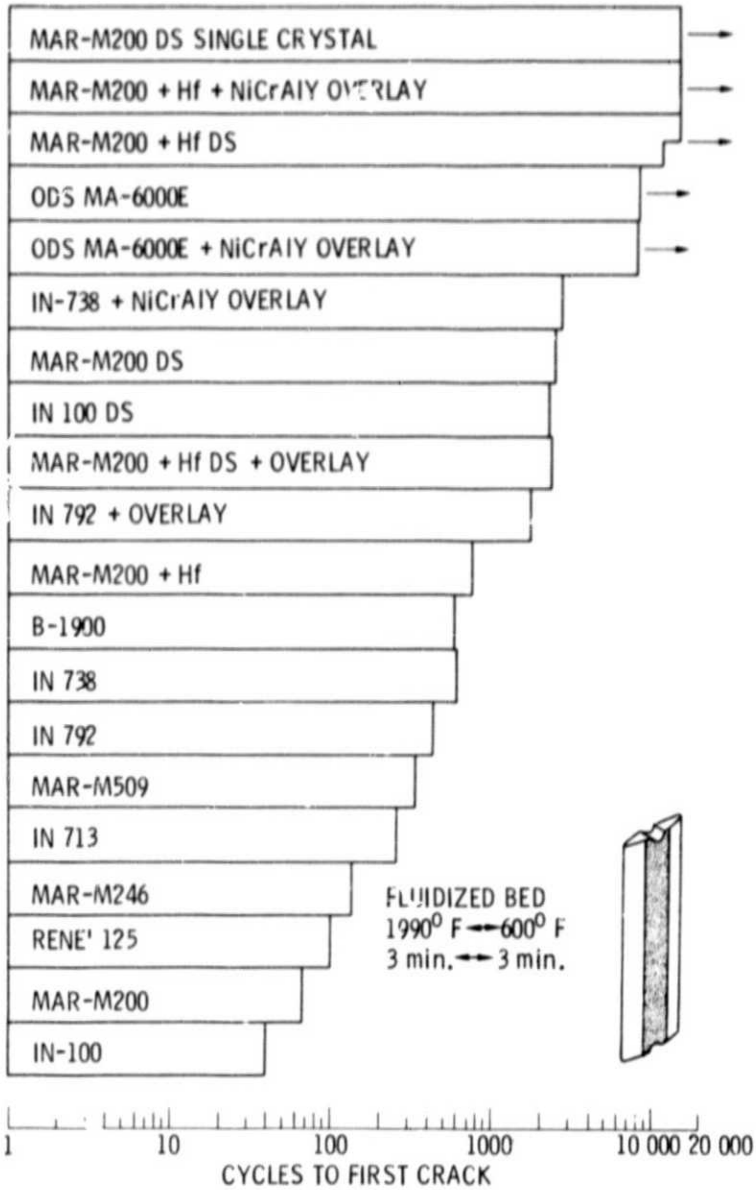

Figure 8. - Fluidized bed thermal fatigue results for superalloys including the oxide dispersion strengthened MA-6000E.

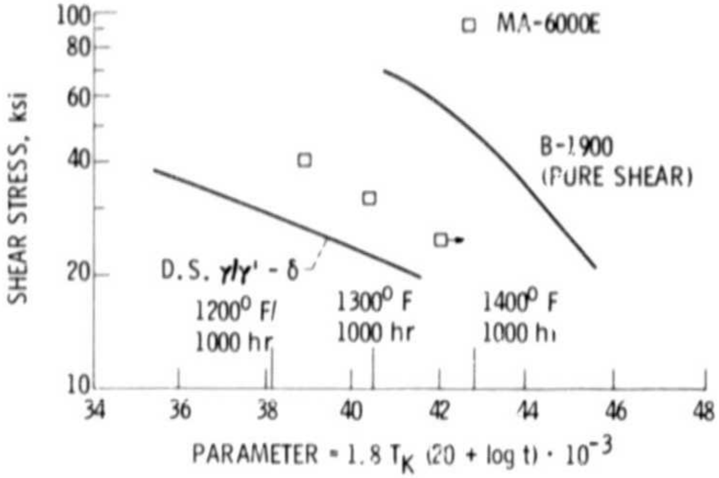

Figure 9. - Creep shear results for MA-6000E for specimens simulating a turbine blade root.