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Progress Toward Determining the Potential of ODS Alloys for Gas Turbine Applications

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ABSTRACT

The Materials for Advanced Turbine Engine (MATE) Program managed by the NASA Lewis Research Center is supporting two projects to evaluate the potential of oxide dispersion strengthened (ODS) alloys for aircraft gas turbine applications. One project involves the evaluation of Incoloy* MA-956 for application as a combustor liner material. An assessment of advanced engine potential will be conducted by means of a test in a P&WA 2037 turbofan engine. The other project involves the evaluation of Inconel* MA 6000 for application as a high pressure turbine blade material and includes a test in a Garrett TFE 731 turbofan engine. Both projects are progressing toward these engine tests in 1984.

INTRODUCTION

The Lewis Research Center has been actively engaged in understanding and developing oxide dispersion strengthened (ODS) nickel-base alloys for over two decades. Over this time period, the nickel-base and iron-base alloy systems have matured to the point where ODS alloys are now a commercial reality. This paper will review two active projects, funded under the NASA Materials for Advanced Turbine Engines (MATE) Program, which are concerned with determining the performance/life potential and problems associated with application of ODS alloys in aircraft gas turbine components. The first project, one to develop improved combustor liners using Incoloy MA 956, is being performed under a contract with Pratt & Whitney Aircraft. The second project, one to develop higher temperature turbine blades using MA 6000, is being performed under a contract with the Garrett Turbine Engine Company. Reviews of both of these projects were presented at "Frontiers of High Temperature Materials"[2,3] in New York City, 1981. This paper serves to update those presentations.

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*Trademark - INCO Alloy Products Company.

Incoloy MA 956 Combustor Liner

Background

The steady increase in gas turbine engine operating temperatures over the past decade has been accomplished at the expense of higher heat fluxes and greater thermal transients in aircraft combustors. These conditions have created a need for an improved durability combustor material. One approach to provide the improved material performance is to exploit the capabilities of a material having a greater temperature capability than the widely used combustor material Hastelloy X* (which is typically used to metal temperatures of only about 870°C). The specific objective of this project is to explore the potential of extending the operational life of combustor liners to four times their current life by using ODS sheet alloys which show about a 170°C temperature advantage over Hastelloy X[4] and thus have improved over-temperature capacity. During the early phases of the project, both Incoloy MA 956 (a yttrium-oxide-dispersion-strengthened FeCrAl) and HDA 8077 (a yttrium-oxide-dispersion-strengthened NiCrAl material) were found to meet the materials requirements for this application. The compositions of these alloys are shown in Table I. Their creep properties, oxidation behavior, and low cycle fatigue behavior are summarized in Figure 1. Figure 2 summarizes the results of hot spot blister tests[4] -- a test used to identify promising combustor materials -- which were performed on both alloys. While Incoloy MA 956 and HDA 8077 showed about equal resistance to deflection, HDA 8077 showed greater resistance to crack penetration in the hot spot blister test.

As the result of additional reproducibility tests conducted at both vendors, however, Incoloy MA 956 was selected for continued evaluation in component tests. This is because the manufacturer of MA 956 (Wiggin Ltd.) successfully produced a second lot of material meeting the previously cited program goals; whereas, the producers of HDA 8077 (Cabot Corporation) experienced processing difficulties which resulted in material with lower stress rupture properties than that of the first lot[4].

Component Thermal Fatigue Tests

A preliminary design evaluation phase was conducted to identify designs suited to the unique properties of MA 956 sheet material. Two segmented-louver-design concepts were selected for further evaluation. These were a mechanically-attached, film cooled, segmented louver and a transpiration cooled, segmented twin-wall design. Both concepts are shown schematically in Figure 3. The thermal fatigue tests for each of these design concepts are pictured in Figure 4. The details of these tests have been previously described by Henricks[4]. These tests were intended to simulate the cyclic thermal operating conditions that each of the designs would be expected to encounter in engine operation and included 10,000 thermal cycles. However, neither test was able to cause severe distress in the MA 956 alloy. In all tests, the ODS alloy suffered significantly less thermal distortion than the baseline Hastelloy X. An example of this is shown in Figure 5a.

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*Trademark - Cabot Corporation.

Both the mechanically-attached, film cooled, segmented louver and the transpiration cooled, segmented, twin wall designs appeared to meet the design objective of the project. The results of the preliminary design study are shown in Table II. A decision to proceed to engine testing with the film cooled, segmented louver was primarily based on its greater similarity to current combustor design practice. To further verify the structural integrity of the concept, additional LCF component tests were performed.

For these additional tests, panels were cycled with hot rivets or structural rivets removed. A sketch of the panels showing hot and structural rivets is shown in Figure 6. Also, to simulate binding rivets, one panel was brazed in place. As before, after 10,000 thermal cycles, no significant distress occurred in the Incoloy MA 956 panels and very little distortion occurred compared to Hastelloy X. These data are summarized in Figure 5b-d.

Engine Test Article

An experimental hybrid combustor segment was designed and is being fabricated for testing in a P&WA 2037 turbofan engine. A sketch of a cross section of the design is shown in figure 7. The two last louvers on the inner annular liner of a bill of materials combustor are being replaced with a mechanically attached film cooled louver fabricated from Incoloy MA 956. The temperature model used to analyze the critical louver segment is shown in figure 8. The maximum metal temperature is estimated to be 1070°C at the hot streak louver lip; the average temperature at the lip of the segment being about 920°C. The maximum stress is circumferential and estimated to be 127 MPa at a temperature of 565°C. This can further be reduced by slotting the panel. It should be noted that the ODS panel design differs from that used in production PWA 2037 combustors. The temperatures and stresses discussed here only apply to the experimental combustor segment for this project. The stress in the Incoloy MA 956 rivets is calculated to be less than 2 MPa. An engine test of this combustor configuration is scheduled for 1984.

MA 6000 Turbine Blades

Background

A traditional means to improve the performance of turbofan engines, as measured by decreases in specific fuel consumption or increases in thrust to weight ratio, has been to increase the turbine inlet temperature. To accommodate such higher temperatures, both turbine airfoil cooling improvements and improved metals properties have been necessary. Thus, continued research on both cooling and materials will pace future engine performance growth.

The first two versions of the Garrett Turbine Engine Company TFE 731 turbofan engines followed a typical engine growth approach. First solid IN 100* turbine blades were used, then air-cooled blades of the same alloy were introduced. The next growth modification, however, involved a shift to solid directionally solidified blades made from MAR M247**, a higher

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* Trademark - INCO Alloy Products Company.
**Trademark - Martin Marietta Corp.

temperature-capability alloy. Future use of uncooled turbine blades at higher operating temperatures by means of an advanced alloy is clearly a desirable approach because of the simplified construction of uncooled turbines and the geometric constraints imposed on complex cooling passages in small turbine blades. The project to be reviewed here involves Garrett's examination of the potential of such uncooled turbine blades through the use of ODS alloy MA 6000.

MA 6000 is a nickel-base alloy strengthened by both a dispersion of yttrium oxide coupled with the precipitation of the ordered face centered cubic compound based on Ni_3Al. This compound is called gamma prime, ('). The composition of MA 6000 is shown in Table III. At a stress of 138 MPa, (a critical stress typical of a small turbine engine blade), the alloy has about an 85°C temperature advantage over directionally solidified alloys such as MAR-M247[2], while at lower temperatures, it is somewhat weaker than MAR-M247. These temperature-strength relationships are shown in Figure 9. The strength-temperature relationships of this ODS material, as compared to a more conventional superalloy, caused a reexamination of airfoil designs as will be discussed later.

Early laboratory development of MA 6000 was in the form of 12 mm diameter rods and 12x25 mm bars. However, a larger size is required to make blades for the TFE 731 turbine. As previously reported[2], INCO scaled up the processing to produce bars of about 18mm x 43mm cross section. That is the size required to allow adequate stock for machining TFE 731 blades. The acceptance criteria for the bar stock are shown in Table IV.

In this program, process scale-up activities were performed at the INCO Research Laboratories at Sterling Forest, New York. Material to be used in the planned engine test and that which is presently being evaluated, however, has been produced at INCO's Wiggin Alloys Ltd., in Hereford, England, where the initial production scale-up MA 6000 is being performed.

Property Characterization

The material which was evaluated early in the project was produced at the INCO Research Laboratories in New York. The tensile, high cycle fatigue, and stress rupture properties were found to be consistent with previously reported results[5,6]. These data were used for the preliminary blade design to be discussed later.

The environmental resistance of MA 6000 to both oxidation and hot salt corrosion was also evaluated. The results are summarized in Figure 10. While the oxidation resistance of MA 6000 is comparable to commonly used nickel-base superalloys, its resistance to hot salt corrosion is superior to these same reference alloys.

Recently, production quantities of MA 6000 became available from Wiggin Alloy Ltd., and detailed evaluation of the alloy's mechanical properties was initiated. This evaluation will include testing of material from at least two lots of MA 6000. Among the tests to be performed are: tensile tests, creep-rupture tests, high cycle fatigue tests, low cycle fatigue tests, and physical property tests. The initial data on production MA 6000 are summarized in figure 11. Transverse tensile data are not shown. However, both tensile and yield strengths were within 10% of the longitudinal strengths. Transverse ductilities however, were lower than those determined in the longitudinal tests and ranged from less than 2% to about 4% elongation and reduction in area. All the data, except the strain controlled LCF data, discussed below, are consistent with data previously obtained in this project or published elsewhere[5-7]. These data clearly support earlier expectations that MA 6000 has potential for use as a high pressure gas turbine blade material.

The LCF data reported here are significantly lower in life those that previously reported[5]. It is possible that the data in reference 5 may be in error as diametral strain control was used in that study. When one attempts to use diametral strain control on MA 6000 (a face-centered cubic alloy having 011 texture in the rolling direction), it has been observed that the elastic Poisson's ratio may vary from near 0 to about 0.6 as the radial orientation of the gage is changed*. This radial anisotropy is consistent with the material having a texture other than 001 in the rolling direction.

No attempt has yet been made to correlate the elastic and plastic anisotropy in MA 6000. A few diametral strain controlled LCF tests at room temperature were performed with the strain gage placed at the orientation of maximum diametral elastic strain.* The plastic Poisson's ratio was assumed to be 0.5 to determine the strain range. These data are also shown in figure 11 -- and agree well with the Garrett data obtained with longitudinal strain control. These data are also consistent with more recent data from INCO.[7]

Component Design and Tests

A turbine blade was designed for evaluation in a TFE 731. The design was based on the data obtained from the early materials tests described previously. Comparison of the stress rupture curve for MA 6000 to a conventional superalloy shows that the advantage for MA 6000 becomes greater as the temperature is increased. To exploit that advantage and to mitigate the lower strength at the lower temperatures, a blade with a taper ratio of 6.25 was selected. The shape of the experimental blade is shown in figure 12.

To evaluate the effects of MA 6000's anisotropy on blade harmonics, a simple tapered plate was machined and holographically tested. The results were then compared with predictions resulting from a computer model. The test sample and typical results are shown in figure 13. The mode shapes and frequencies are in reasonable agreement with predictions. Thus, for the proposed blade, no unusual HCF problems are anticipated.

Because of the high anisotropy of the MA 6000, there was concern about the adequacy of conventional blade-to-disk attachment designs. It has been reported that the ratio of the shear strength to the ultimate tensile strength of ODS and other alloys showing high anisotropy is lower than that of conventional superalloys[8]. Firtree mechanical tests were therefore performed. The test configuration and results are shown in Figure 14. The test section has the geometry of the TFE 731 firtree. Tensile tests, stress rupture tests, and LCF tests were performed at 760°C. Tensile tests were also performed at 650°. Not shown in figure 14 are the firtree stress rupture tests which showed the average rupture strength to be about 85% of the longitudinal stress rupture strength. In general, all the results show that while MA 6000 may be more prone to shear failure in tension and stress rupture than conventional alloys, a conventional firtree design can accommodate the loads.

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*Private Communication - M. McGaw, Lewis Research Center.

CONCLUDING REMARKS

This has been a progress report on two projects examining the potential of ODS alloys for gas turbine applications. These projects are funded under the NASA MATE Program. The project aimed at improving the durability of combustor liners is being performed by the Pratt & Whitney Aircraft Corporation. Incoloy MA 956 was selected for experimental component LCF testing and fabrication of a hybrid combustor segment to be evaluated in a P&WA 2037 engine. This component is scheduled to be engine tested in 1984. Only the fabrication of the combustor segment and its testing remain to be accomplished.

The second project involving oxide dispersion strenthened materials is being performed by the Garrett Turbine Engine Company. This project has as its objective exploring the potential of MA 6000 as an uncooled blade material capable of allowing increases in the turbine inlet temperature. The project has generated mechanical property data which, coupled with special component tests, have led to the design of an experimental blade for evaluation in the high pressure turbine of a TFE 731 engine in 1984. While considerable mechanical and physical property testing remains, all data to date support the original thesis that MA 6000 should perform well as a turbine blade material.

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4. Henricks, R. J.: Advanced Oxide Dispersion Strengthened Sheet Alloys for Improved Combustor Durability, Aircraft Engine Diagnostics, NASA CP-2190, 1981, pp. 119-136.
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6. Kim, Y. G.; and Merrick, H. F.: Characterization of an Oxide Dispersion Strengthened Superalloy, MA 6000E, for Turbine Blade Applications. NASA CR-159493, May 1979.
7. Inconel Alloy MA 6000, INCO MAP Mechanically Alloyed Products. INCO MAP, Huntington, WV.
8. Glasgow, T. K.: Creep Shear Behavior of the Oxide Dispersion Strengthened Superalloy MA 6000E. NASA TM-82704, 1981.

TABLE I. - COMPOSITION OF COMBUSTOR CANDIDATE ODS ALLOYS

	Fe	Ni	Cr	Al	Ti	Y_2O_3
Incoloy MA 956	Bal	---	20.0	4.5	0.5	0.5
HDA 8077	---	Bal	16.0	4.0	---	.8

TABLE II. - LIFE/COST COMPARISON OF DESIGNS[a] (MA 956)

	Cooling[b] air, percent W_{AB}	Total strain range, percent	Life[b] cycles/hr	Cost[b]	Weight[b], lb	MC[b]	Change in DOC, percent
JT9D base	1.0	~0.40	1.0	1.0	1.0	1.0	Base
Film cooled, segmented louver	1.0	.145	4x	1.26x	1.06x	.63x	-0.21
Segmented twin wall	.73	.225	4x	1.48x	1.03x	.65x	-.21

[a] Ref. 4
[b] Relative value, i.e., (Value/Value for JT9D)
MC = Maintenance Cost
DOC = Direct Operating Cost

TABLE III. - COMPOSITION OF TURBINE BLADE CANDIDATE, MA6000

	Nominal chemistry, weight percent
Cr	15
Mo	2
W	4
Ta	2
Al	4.5
Ti	2.5
C	.05
B	.01
Zr	.15
Y_2O_3	1.1 (2.5 v/o)
Ni	Bal.

TABLE IV. - ACCEPTANCE CRITERIA FOR 18 mm x 50 mm MA6000 BARSTOCK

Microstructure: Substantially free of porosity and chemical heterogeneity at an optical magnification of 100X.

Macrostructure: Exhibits a coarse elongated grain structure with an average grain aspect ratio of 5:1 or greater and average grain diameters of about 0.5 to 10 mm.

Stress-Rupture Properties

Longitudinal: 2000° F at 20 ksi for 100 hours - Elongation 3 percent
1400° F at 72 ksi for 100 hours - Elongation 4 percent

Transverse: 2000° F at 6 ksi for 100 hours - Elongation 2 percent
1400° F at 42 ksi for 100 hours - Elongation 3 percent

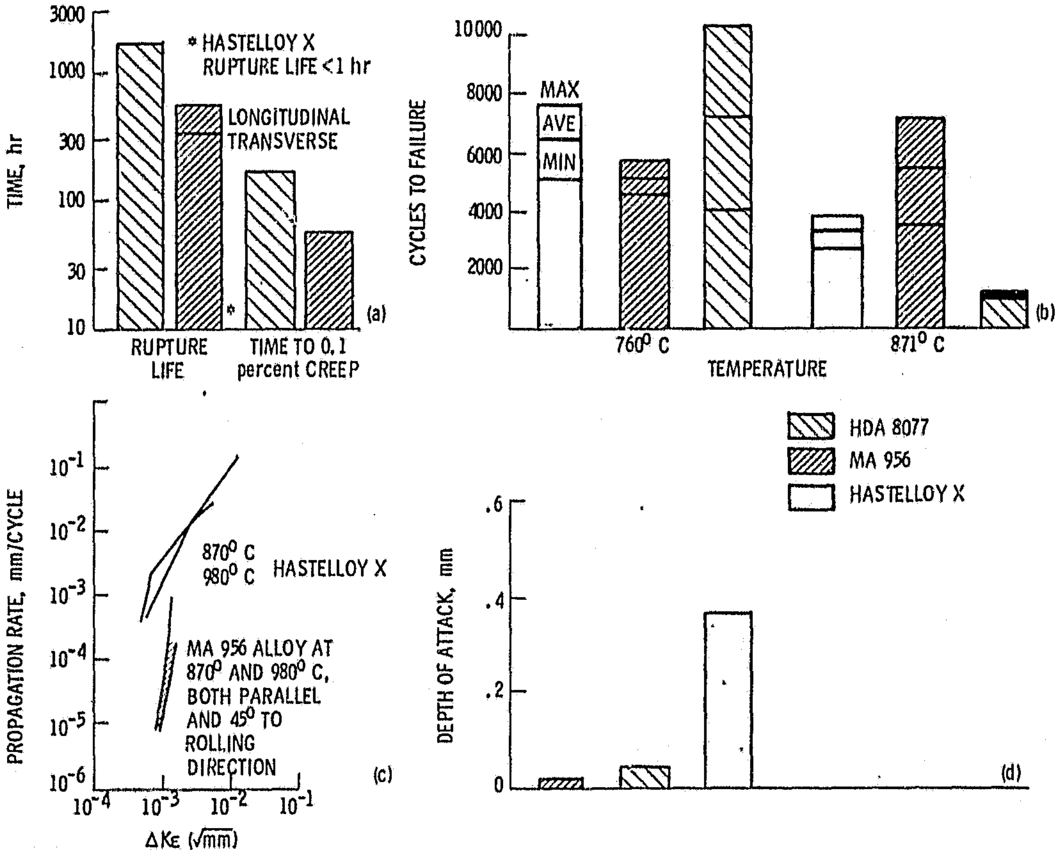
1400° F Tensile Properties

Longitudinal:

0.2 percent YS	UTS	Percent EL	Percent RA
100 ksi	120 ksi	4	5

Transverse:

0.2 percent YS	UTS	Percent EL	Percent RA
100 ksi	120 ksi	3	2



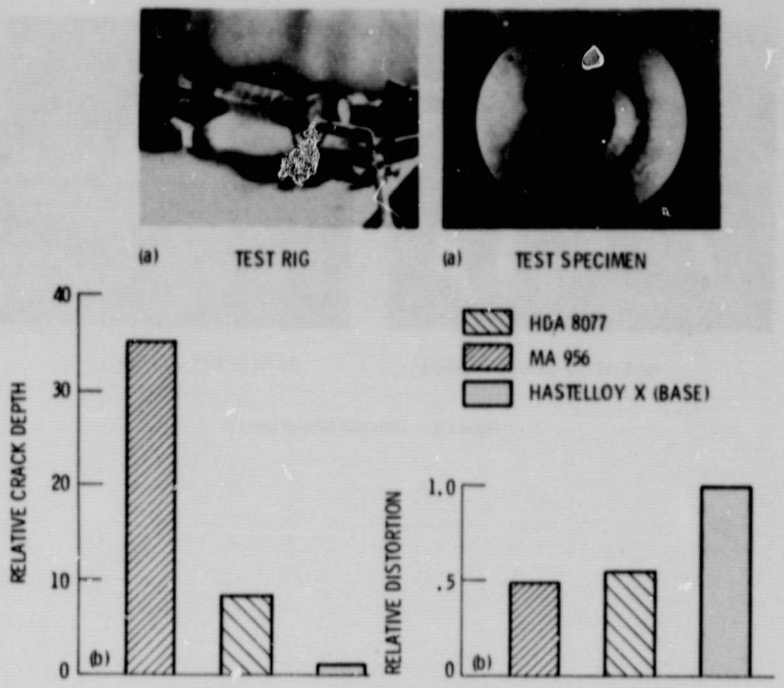
(a) Creep-rupture. Temperature, 980° C; stress, 70 MPa.

(b) Low-cycle fatigue. Strain, ±0.25 percent; cycling frequency, 40 per minute.

(c) Crack propagation. Test temperatures, 870° C and 980° C.

(d) Oxidation attack. Time, 6 minutes; temperature, 970° C.

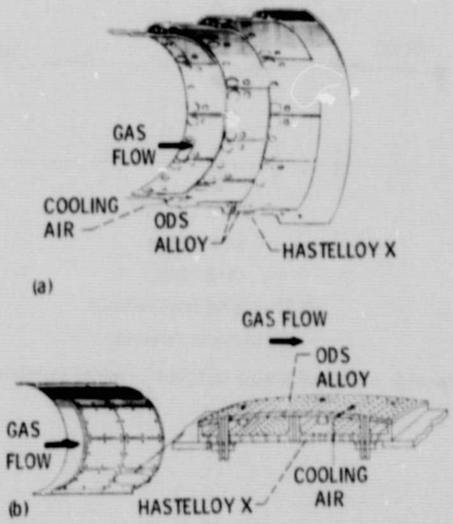
Figure 1. - Mechanical and oxidation properties of MA 956, HDA 8077, and Hastelloy X alloys.



(a) Test rig and specimen.

(b) Crack penetration and material distortion.

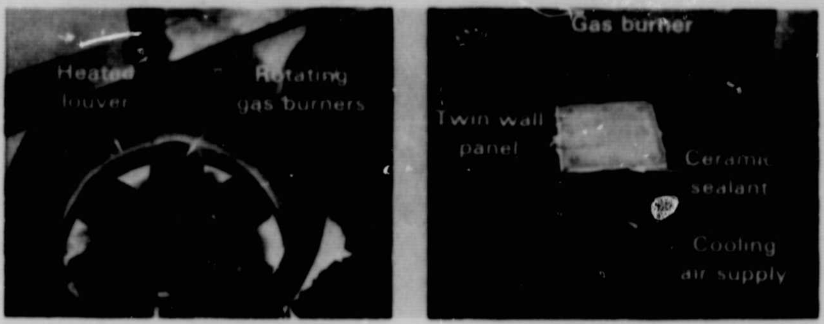
Figure 2. - Hot-spot blister thermal-fatigue test. Temperature cycle, 540° to 980° C; number of cycles, 500.



(a) Mechanically attached, film cooled segmented louver.

(b) Transpiration cooled, segmented twin-wall design.

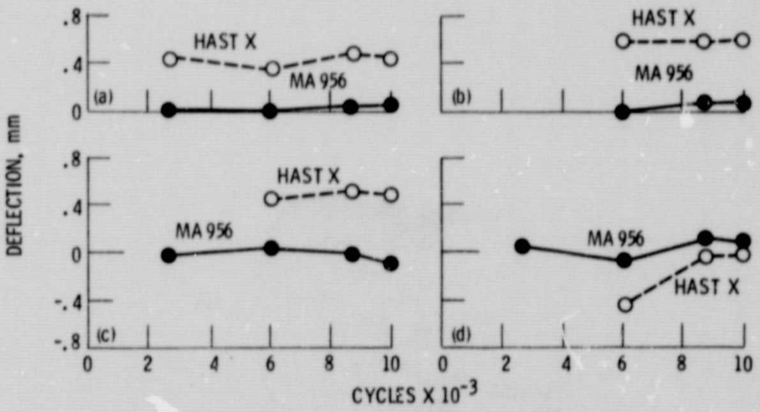
Figure 3. - Segmented combustor liner concepts.



(a) RIVETED LOUVER THERMAL CYCLE TEST.

(b) TWIN WALL LCF TEST.

Figure 4. - Thermal fatigue tests.



(a) Baseline.

(b) Brazed.

(c) Structural rivet removed.

(d) Hot rivets removed.

Figure 5. - Thermal fatigue tests of film cooled segmented louver.

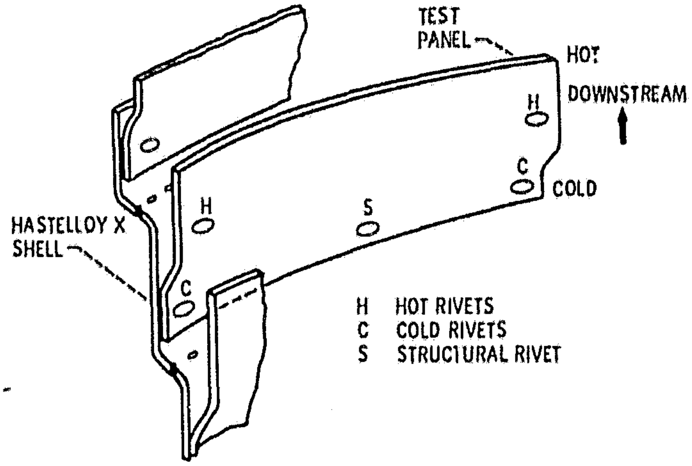


Figure 6. - Thermal fatigue test panel

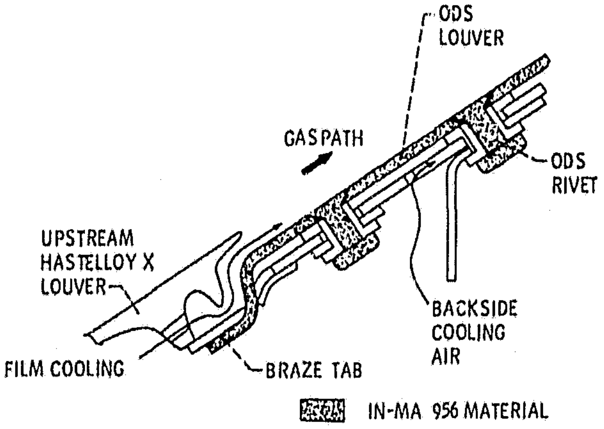


Figure 7. - Cross section of experimental ODS combustor.

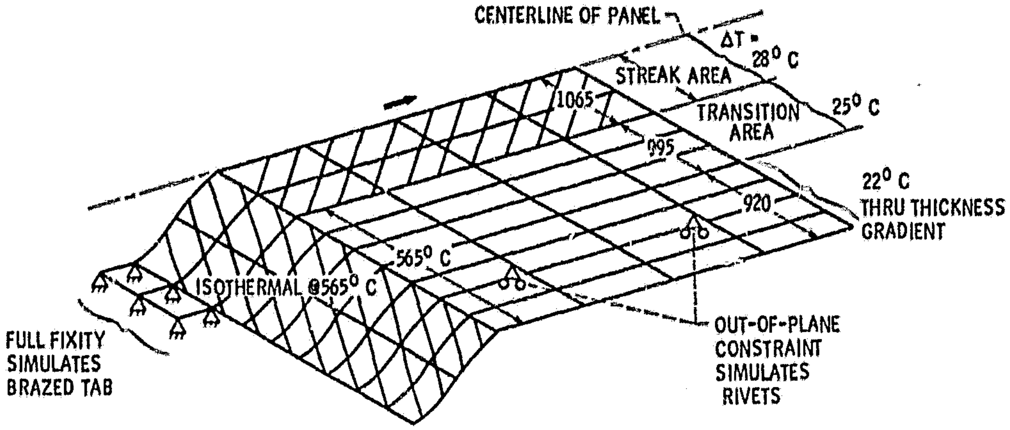


Figure 8. - Finite element model of experimental MA 956 louver.

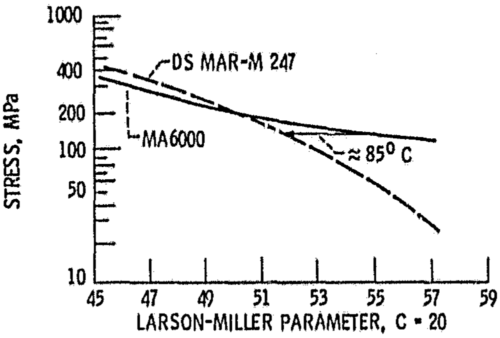
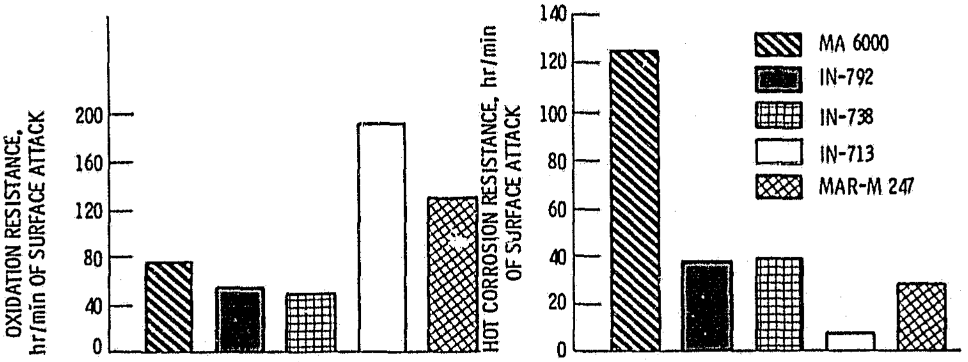


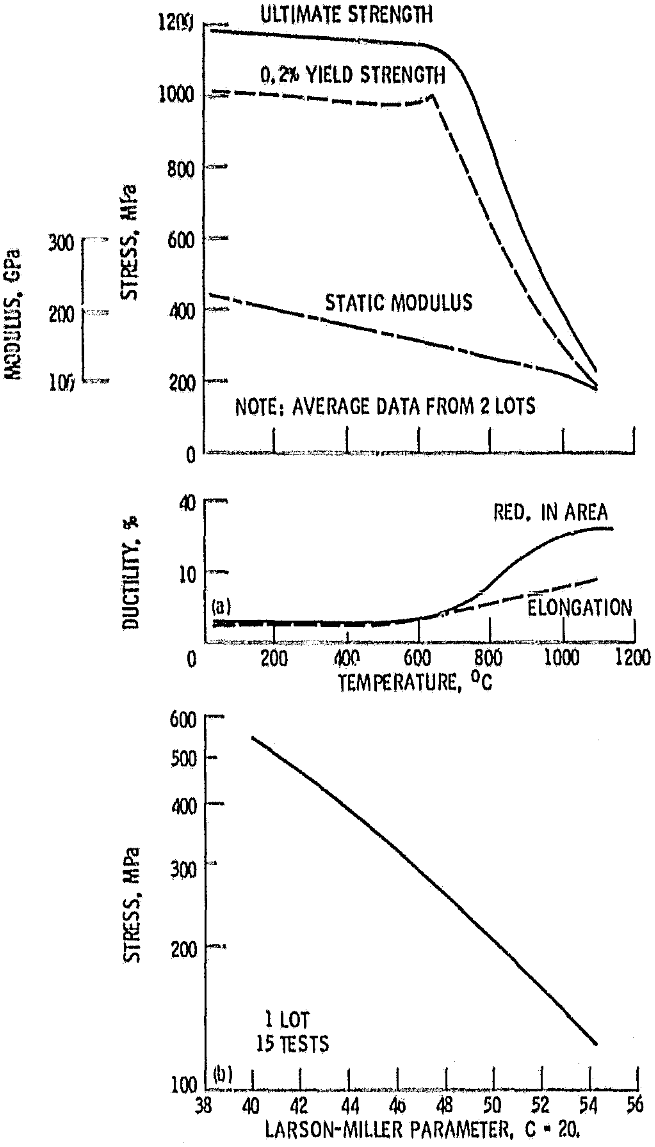
Figure 9. - Stress-rupture strength of MA6000.



(a) Oxidation. Time, 400 hr; temperature, 1095° C.

(b) Hot corrosion. Time, 250 hr; temperature, 925° C; salt concentration, 5 ppm.

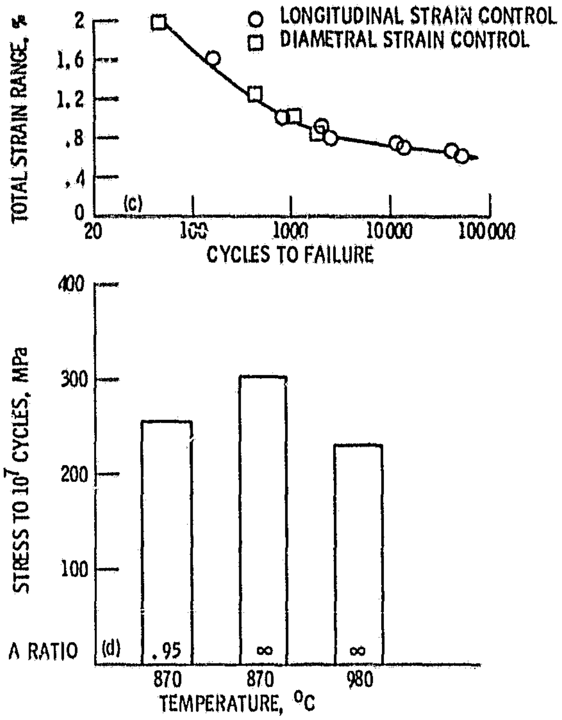
Figure 10. - Environmental resistance of alloys tested in cyclic burner rig.



(a) Longitudinal tensile.

(b) Stress rupture behavior.

Figure 11. - Properties of initial production MA6000.



(c) 760° C low cycle fatigue.

(d) 10^7 High cycle fatigue.

Figure 11. - Concluded.

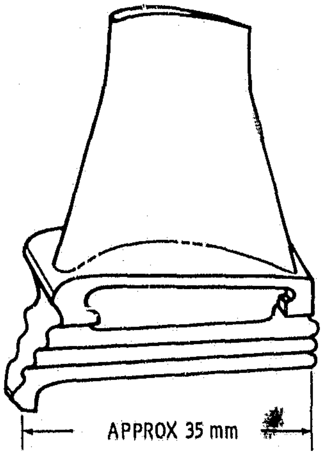
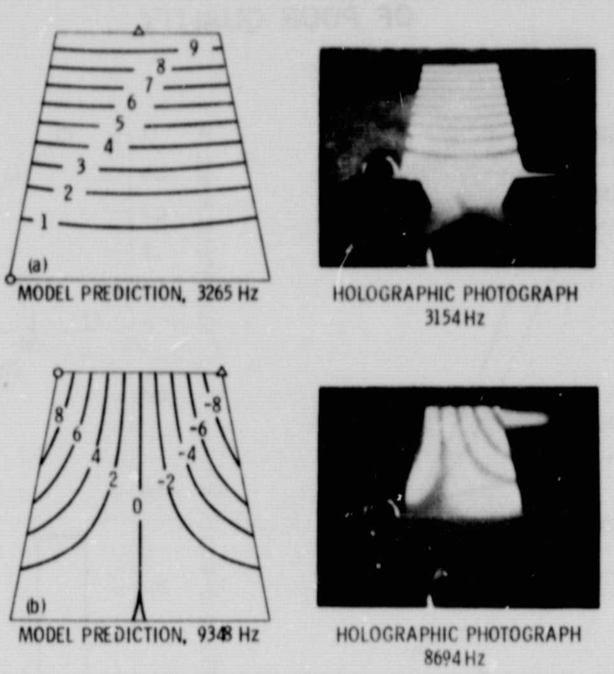


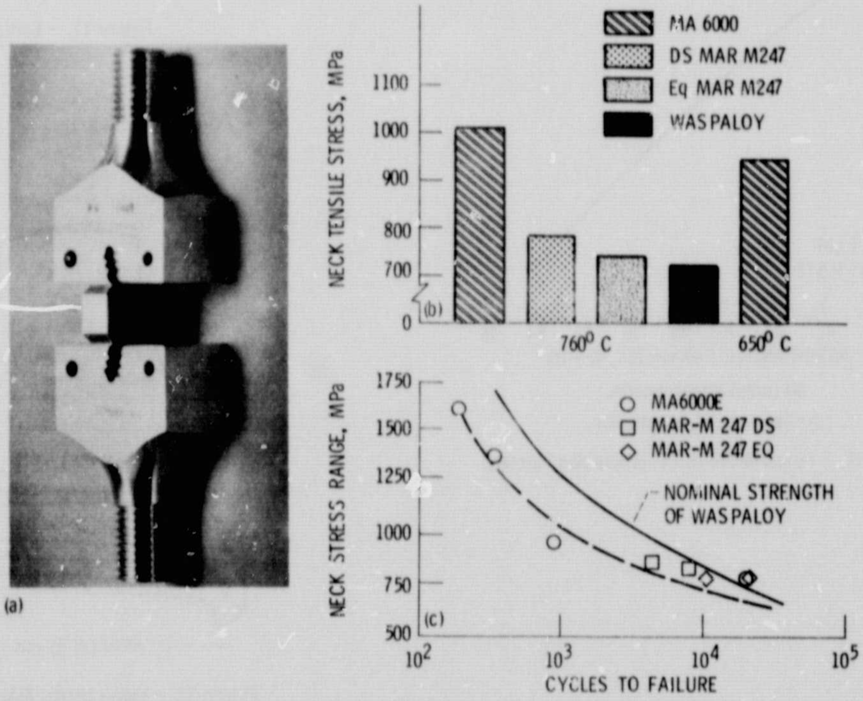
Figure 12. - Experimental MA6000 high pressure turbine blade for TFE 731 engine.



(a) First flexural mode.

(b) First torsion mode.

Figure 13. - Blade model vibration study.



(a) Test specimen.

(b) Firtree tensile test.

(c) Firtree low cycle fatigue.

Figure 14. - Firtree tests.