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CERAMIC LIFE PREDICTION METHODOLOGY - ANALYTICAL
ASSESSMENT OF SELECTED COMPONENT DATA(U) FORD MOTOR CO
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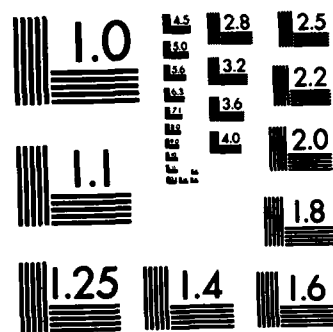
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CERAMIC LIFE PREDICTION METHODOLOGY -
ANALYTICAL ASSESSMENT OF SELECTED COMPONENT DATA

September 1982

L. R. SWANK
Ford Motor Company
Dearborn, Michigan 48121

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ABSTRACT

A complete set of thermal conditions, mechanical loads, geometry as well as thermal, elastic, fast fracture, and time dependent material properties was furnished by AMMRC for the hub of a gas turbine disc. A finite element computer model was prepared for the disc from this data. The temperature and stress distributions, the fast fracture and the time dependent reliabilities were calculated. The results were presented in iso-stress and iso-thermal plots and in graphical data.
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Foreword

This report represents the analysis of a structural ceramic component selected by AMMRC. The component selected was the hub of a hot pressed silicon nitride turbine rotor. The required geometrical, material, strength, and time dependent data was supplied by AMMRC. This work was conducted as part of the "Methodology for Ceramic Life Program," initiated by Dr. Robert Schulz of the Office of Conservation, division of Transportation Systems, Department of Energy, and monitored by the Army Materials and Mechanics Research Center under Contract Number DAAG-46-77-C-0028. This work was part of the continuing investigation of analytical and experimental methods in ceramic life prediction aimed toward utilizing structural ceramics in high temperature applications. The principal investigator of this program was R. R. Baker, Ceramic Materials Department, engineering and Research Staff, Ford Motor Company. The technical monitor was Dr. E. M. Lenoë of AMMRC. The author wishes to thank Drs. E. M. Lenoë and R. N. Katz of AMMRC for suggestions in carrying out the program.

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1. INTRODUCTION

This report presents the analysis of a gas turbine disc based on data supplied by AMMRC. The data supplied was the disc's geometry, its rotational speed, forces to simulate the blade loads, heat transfer coefficients and corresponding fluid temperature. Also supplied were the material's elastic, fast fracture, and time dependent properties.

The primary purpose of the analysis was to calculate reliability versus time for the steady state speed and temperature conditions. The time dependent theory used is explained in Section 2. In order to complete a time dependent reliability analysis it is necessary to calculate the reliability at time equals zero which is the fast fracture reliability. Weibull theory was used for calculation of fast fracture reliability and the theory is briefly reviewed in Section 3.

The stresses and temperatures were calculated with finite element computer programs and the results are plotted in contour plots. For reference the stresses due to mechanical loads at room temperature were calculated and plotted. The data supplied by AMMRC was reproduced here in the tabular form required by the computer codes used in the analysis.

2. TIME DEPENDENT THEORY

The prediction of time to failure in structural ceramics is usually based on the equation

$$V = AK_I^n \quad (1)$$

This equation relates the velocity of a crack in the material to the stress intensity factor of the tip of the crack. Sivers(1) observed this behavior in steel and published velocity versus stress intensity data and fitted the constant "A" and crack velocity exponent "n" to the data with linear regression analysis(2). Evans(3) observed similar behavior in ceramic materials and using the fracture mechanics equation

$$K_I = \sigma Y a^{1/2} \quad (2)$$

arrived at the following equation for calculating crack growth versus time(4).

$$\int_0^t AY^n \sigma^n dt = \frac{2}{(n-2)} \left[\left(\frac{1}{a_0} \right)^{\frac{n-2}{2}} - \left(\frac{1}{a} \right)^{\frac{n-2}{2}} \right] \quad (3)$$

Equation 3 applies only to a single crack in a uniform stress field. To allow calculation of time dependent failure in complex structures, Paluszny(5) combined the ideas in Equation 3 with the Weibull(6) equation for calculating fast fracture reliability in brittle materials and arrived at Eqn. 4.

$$R = \exp \left[- \left[\left(\ln \left(\frac{1}{R_{ff}} \right) \right)^{\frac{n-2}{m}} + \frac{\sigma_t^n}{\sigma_\theta^{n-2} B} \right]^{\frac{m}{n-2}} \right] \quad (4)$$

Equation 4 was reduced to Eqn. 5 in Reference 7.

$$R = R_{ff} \left(1 + \frac{\sigma_t^n}{B} \right)^{\frac{n-2}{m}} \quad (5)$$

In this study Eqn. 5 was used to calculate the reliabilities versus time of complex structures by dividing the structure into small elements where the stress was considered constant and evaluating Eqn. 5, the reliability of a structure with "q" elements was then calculated with Eqn. 6.

$$R = R_1 \cdot R_2 \cdot R_3 \dots R_q \quad (6)$$

This technique is suitable for use with finite element stress programs where R_1 is evaluated for each element. The constant in Eqn. 5 is given as Eqn. 7(5).

$$B = \frac{2}{(n-2)Y^2 AK_{IC}^{n-2}} \quad (7)$$

Equations 5, 6, and 7 were used in this report to calculate time dependent reliability.

3. WEIBULL THEORY

The evaluation of Eqn. 5 requires that the fast fracture reliability be evaluated. For this study, the Weibull(6) equation was used. Weibull proposed that each element of a structure has a definite probability of failure and that the entire structure could be considered to be an assembly of the individual elements and their associated probability of failure. Vardar and Finnie(8) give an integral formulation of the Weibull approach:

$$P_f = 1 - \exp^{-B} = 1 - \exp \left[- \int_V (K \int_A \sigma_n^m dA) dV \right] \quad (8)$$

The term in the parentheses is evaluated on the surface of the unit sphere (Fig. 1), over the regions where the normal stress is tensile and neglecting regions where the normal stress is compressive. The reasons for neglecting compressive stress are 1) for structural ceramics, compression is not as detrimental in causing fracture as is tension, and 2) mathematical complexities are minimized(9). The normal stress on the surface of the unit sphere in terms of the maximum principal stresses and the polar and azimuthal angles is given by:

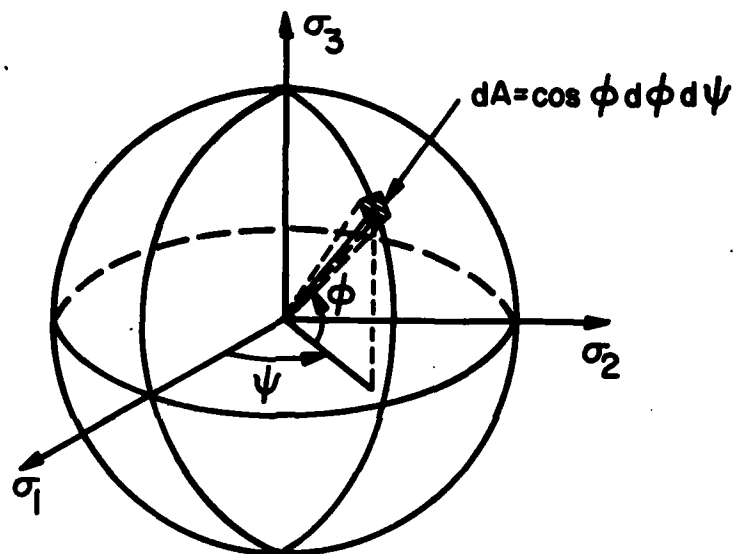


Fig. 1. Geometric variables describing location on unit sphere

$$\sigma_n = \cos^2 \phi (\sigma_1 \cos^2 \psi + \sigma_2 \sin^2 \psi) + \sigma_3 \sin^2 \phi \quad (9)$$

The constant, K , is given by:

$$K = \frac{2m + 1}{2\pi \sigma_0^m} \quad (10)$$

The $(2m+1)/2\pi$ term in Eq. 10 is a compatibility factor required to make the result of integrating Eq. 8 using the normal stress distribution of Eq. (9) for uniaxial stress cases, agree with the results obtained from the one-dimensional Weibull equation:

$$P_f = 1 - \exp \int_V \left(\frac{\sigma}{\sigma_0} \right)^m dV \quad (11)$$

The integration of Eq. 8 over an entire structure is accomplished by dividing the structure into finite elements in which the principal stresses can be assumed to be constant. The result of integrating over the unit sphere is constant in each finite element; therefore, the risk of rupture for each element is simply the volume of the element times the integrated result over the unit sphere. This procedure is very convenient when used with finite-element stress programs and is the one used to calculate the probability-of-failure distributions for the structures in the present paper.

In the Weibull formulation, σ_0 and m are parameters which show the probability of having a certain strength in any finite element. The values of σ_0 and m are obtained from experimental test results. Weibull showed that the characteristic strength, σ_0 , is identical to the ultimate strength of the material in the classical theory as the Weibull modulus, m , increases indefinitely. This result provides a physical interpretation of the characteristic strength. The Weibull modulus may be interpreted as a measure of variability in the strength distribution; as m increases, the variability of the strength diminishes.

For this report value of σ_0 was calculated with Eqn. 12(10).

$$\sigma_0 = \text{MOR}_0 \left(\frac{bh}{2} \right)^{1/m} \left[\frac{L_1 + mL_2}{(m+1)^2} \right]^{1/m} \quad (12)$$

The parameters σ_0 and m define the strength of the material and are independent of the volume and geometry of the structure. They are the values used to determine the failure distribution of a complex structure and are generally determined from MOR bar tests. It is important to note that the MOR is not an intrinsic material parameter but depends on the geometry of the MOR bar and test fixture. A convenient formula for scaling the MOR value from one geometry and test fixture to another is:

$$\frac{\text{MOR}_B}{\text{MOR}_A} = \left(\frac{b_A h_A}{b_B h_B} \right)^{1/m} \left(\frac{L_{A1} + mL_{A2}}{L_{B1} + mL_{B2}} \right)^{1/m} \quad (13)$$

The subscripts here identify bar and fixture A and bar and fixture B. This formula assumes four-point loading with the inner span place symmetrically with respect to the outer span. This formula was used to scale the MOR values furnished by AMMRC to standard "A-size" MOR values. The Weibull equation has been shown to be very effective for predicting the experimental failure distributions of complex structure from data bases obtained on MOR bar tests(8), (10).

4. FINITE ELEMENT MODEL

The finite element model set up to simulate the hub is shown in Fig. 2. It has 216 elements and 243 nodes. The elements and nodes are numbered horizontally from right to left, starting at the bore. Element numbers are located in the center of the element, and node numbers are shown on the exterior of the grid. Node numbers 236, 237, 238, 240, 241, and 242 were located with respect to the centerline to coincide with the location of the forces used to simulate the blade loads. Not all node and element numbers are shown on the mesh in Fig. 2., but any one may be located by counting horizontally. The node and element numbers are needed for interpreting the forces used to simulate blade loads and the heat transfer data.

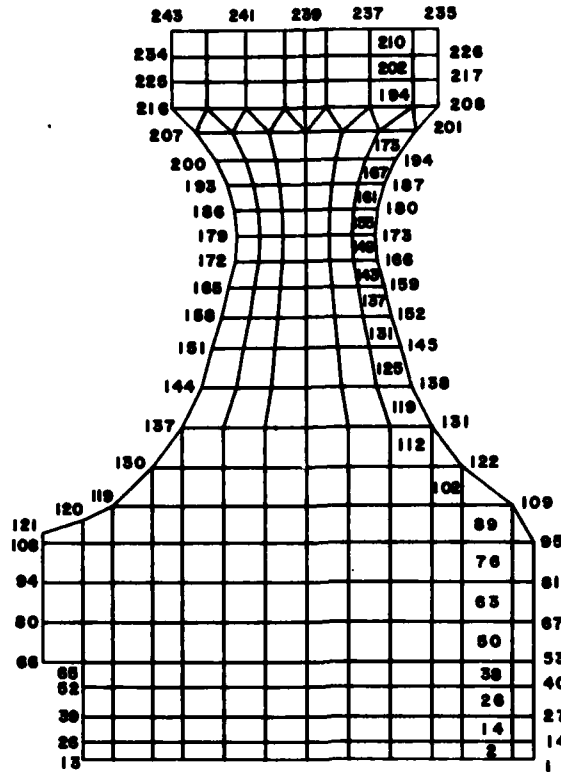


Fig. 2. Disk finite element grid.

5. MATERIAL DATA

The calculation of temperatures, stresses, fast fracture and time dependent reliabilities requires a number of material properties. These properties were supplied by AMMRC or it was suggested that a particular property was similar to the property of a known material. The properties used are given in the Appendix B. AMMRC suggested that the thermal properties of Norton's NC-132 be used and thus the thermal properties given in Table I are for NC-132.

The elastic properties are given in Table II. Young's modulus, Poisson's ratio, and shear modulus were furnished in graphical form and are reproduced here in tabular form. The coefficient of thermal expansion was furnished in tabular form, Table II.

AMMRC furnished modulus of rupture data, giving the values for 50% probability of failure; however, the size of the MOR bar was not that of a standard "A" size bar. This required two conversions to get the MOR bar data into the values accepted by Ford's codes for calculating fast fracture reliability. First the characteristic MOR was calculated from Eqn. 14

$$P_f = 1 - \exp - \frac{(\text{MOR})^m}{\text{MOR}_0^m} \quad (14)$$

where $P_f = 0.5$, $\text{MOR} =$ the value furnished for 50% probability of failure, and $m=15$. The results were then scaled to the standard "A" size bar using Eqn. 13, which with the bar dimensions and the given Weibull modulus of 15 becomes

$$\frac{\text{MOR}_B}{\text{MOR}_A} = 1.0367 \quad (15)$$

The results after these two conversions are presented in Table III.

The time dependent material properties are given in Table IV. The values were furnished for 1100, 1150, 1200, and 1250°C. Most of the computed temperatures in the disc were below 1100°C, with temperatures down to 787°C. Since values of B and n are required at all temperatures the B and n values furnished for 1100°C were assumed to apply down to room temperature. The alternate approach in the absence of values for B and n is to use a lower limit on temperature below which no crack growth is assumed to occur. This approach was not used in this report, since a lower limit was not furnished. The value of B furnished was assumed to be the one obtained from the application of Eqn. 7.

6. MECHANICAL STRESSES

The primary purpose of this report is to calculate time dependent reliabilities and the associated temperatures and stresses; however, for interpreting the results it is useful to have the stresses due to centrifugal effects. This section presents these stresses at room temperature. Table V shows the forces used to simulate blade loads and the node number at which the particular load was applied. This data was furnished in tabular form by AMMRC. The mesh was constructed so that the nodes were located to correspond with the geometric location. The forces were applied radially outward at these nodes.

The rotational speed at which the stresses were calculated was 61,500 rpm. The maximum principal stresses are plotted in Fig. 3. The bore stress is 165 MPa, and the neck stress is 125 MPa. The tangential and radial stresses are plotted in Figs. 4 and 5 respectively. The isostress plots are in increments of 5 MPa. The fast fracture probability of failure for these stresses and the Weibull data given in Table III is 3.725×10^{-8} .

7. COMBINED THERMAL AND MECHANICAL STRESSES

This section presents the results of the analysis of the combined thermal and mechanical stresses. In the analysis a steady state temperature distribution and no creep was assumed. The heat transfer data furnished was in graphical form. In order to input the data into the computer code it was necessary to convert the data into numerical

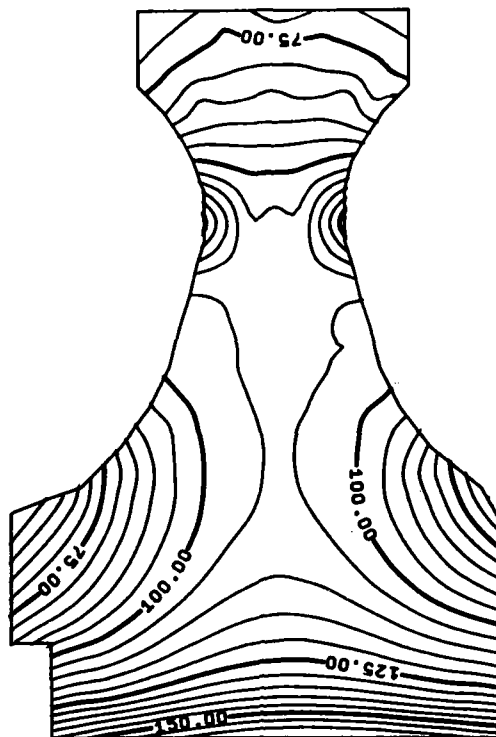


Fig. 3. Maximum principal stresses [MPa] in disc, centrifugal stresses.

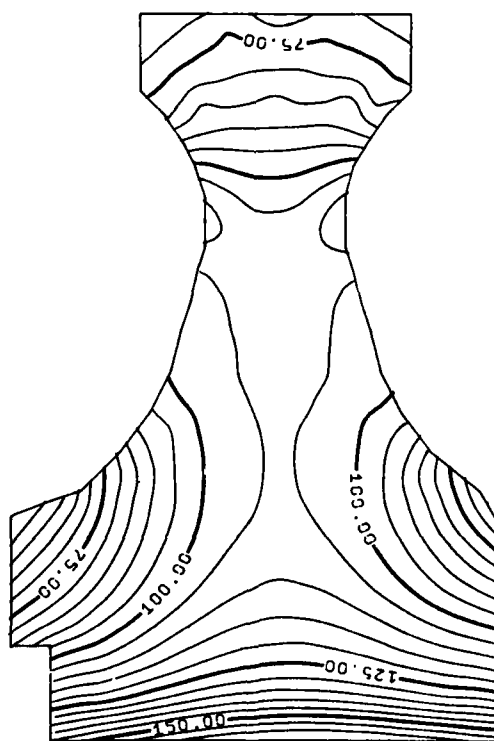


Fig. 4. Tangential stresses [MPa] in disc, centrifugal stresses.

form. Table VI gives the data as prepared for the computer. Shown are the heat transfer coefficients and adiabatic wall temperatures and the corresponding element and node numbers. Data was supplied for the pedestal, and upstream and downstream faces of the disc. The data furnished assumed no heat transfer in the bore and at the attachments; therefore, all surfaces not listed in Table VI were treated as being adiabatic. The steady state temperatures calculated from these boundary conditions are plotted in Fig. 6. Temperatures shown are in degrees centigrade, and the maximum calculated nodal temperature is 1121°C at node 216.

The combined stresses due to the thermal gradients shown in Fig. 6 and the centrifugal loads given in the previous section were calculated and were plotted in Figs. 7, 8, and 9. These are the maximum principal, tangential, and radial stresses, respectively. The maximum bore stress is 220 MPa and the maximum stress in the neck is 200 MPa. The gradient between the isostress lines is 5 MPa.

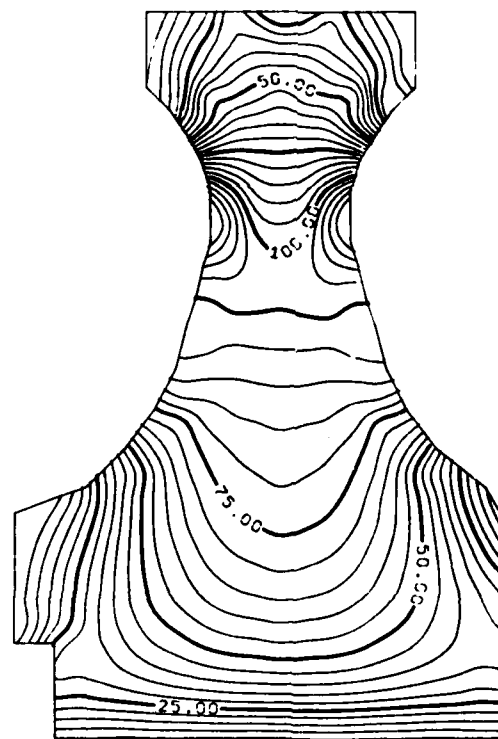


Fig. 5. Radial stresses [MPa] in disc, centrifugal stresses

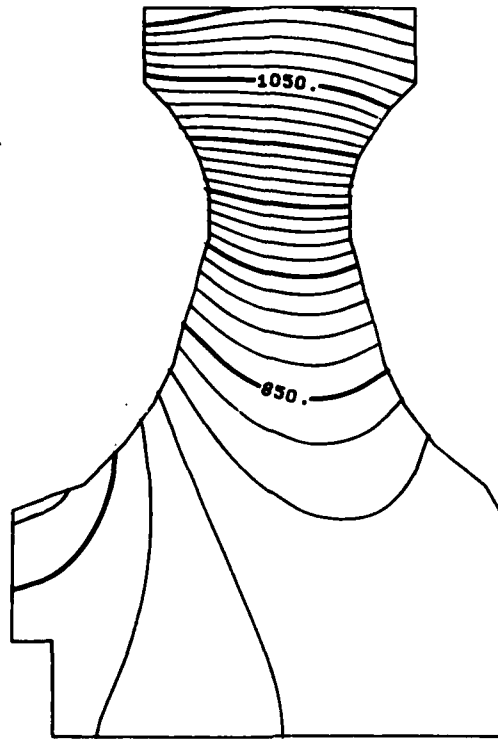


Fig. 6. Isotherms [$^{\circ}\text{C}$] in disc of 61500 rpm.

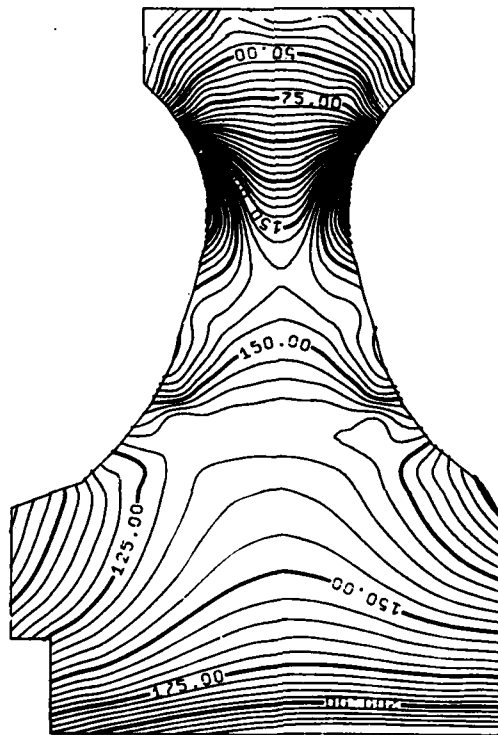


Fig. 7. Maximum principal stresses [MPa] in disc, combining thermal and centrifugal stresses at 61500 rpm.

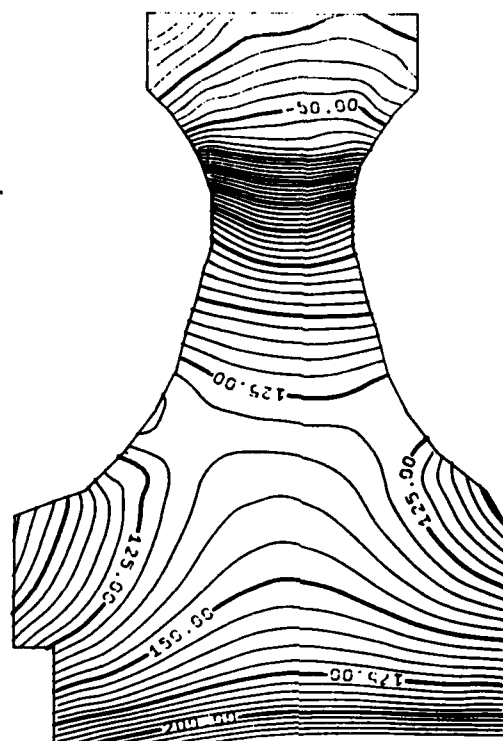


Fig. 8. Tangential stresses [MPa] in disc combining thermal and centrifugal stresses at 61500 rpm.

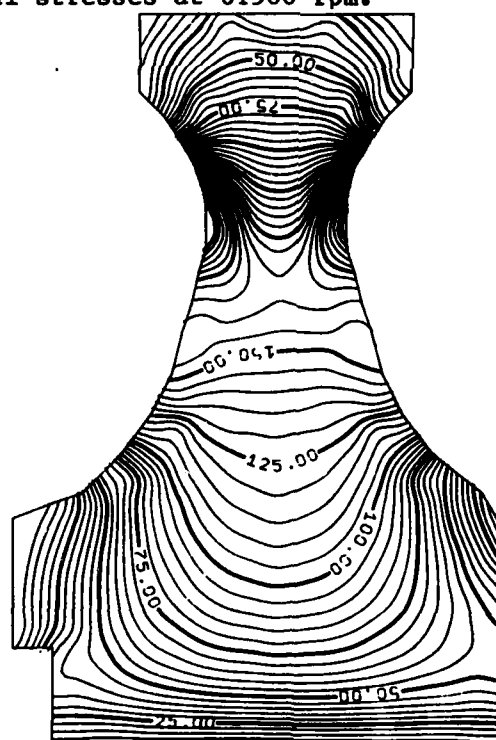


Fig. 9. Radial stresses [MPa] in disc, combining thermal and centrifugal stresses at 61500 rpm.

8. RELIABILITIES

The reliability versus time for the disc was calculated for up to 1000 hours of steady state running and the result is plotted in Fig. 10. The fast fracture reliability, that is the reliability at time equal zero, is 0.99982. The time dependent parameters used are in Table IV. The results assume continuous operation at 61500 rpm at the temperatures shown in Fig. 6. The effects of creep and oxidation are assumed to be negligible. The maximum principal stress in the bore 225 MPa at a temperature of 823°C. The reliability for steady state running at these conditions is at time equal zero, 0.99982, and at time equal 1000 hours, 0.667.

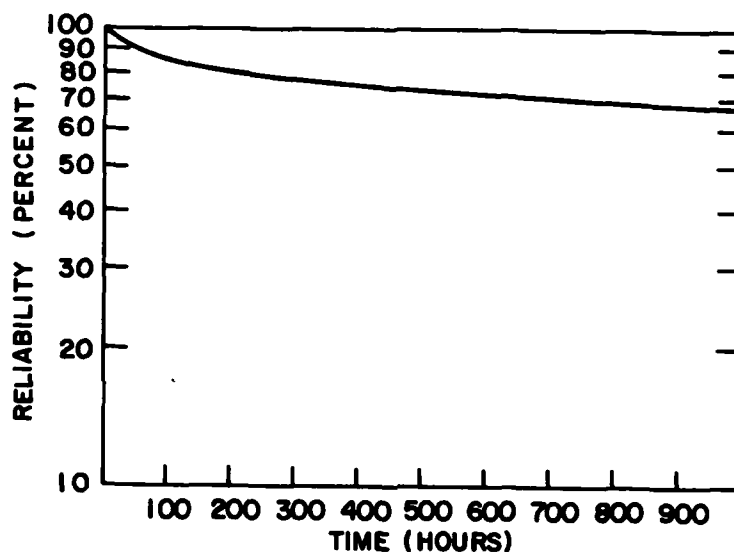


Fig. 10. Reliability versus time for steady state operation.

9. SUMMARY

The mechanical stresses and combined mechanical and thermal stresses were calculated for a hot pressed silicon nitride turbine disc. At room temperature the maximum principal stress was 165 MPa due to mechanical loads at 61500 rpm. The corresponding fast fracture probability of failure was 3.725×10^{-8} . The steady state temperature distribution was calculated for the boundary conditions at 61500 rpm. The maximum temperature in the bore was 824°C, the maximum temperature in the neck was 946°C, and the maximum temperature on the platform was 1121°C. The thermal stresses due to this temperature distribution were combined with the stresses due to mechanical loads at elevated temperatures. At these conditions the maximum principal stress in the bore was 225 MPa at 823°C, and the maximum principal stress in the neck was 210 MPa at 929°C.

The reliabilities versus time were calculated, assuming no creep and continuous running at 61500 rpm, for the combined stress and steady state temperature conditions. At time equal to zero the calculated reliability is 0.99982 and at 1000 hours the reliability is 0.667.

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11. APPENDIX A NOMENCLATURE

- a Crack length, m
- a_0 Initial crack length, m
- A Area on unit sphere, m^2
- A Premultiplier in crack velocity equation, meter/second $(MPa \cdot m)^n$
- B Constant in reliability versus time equation, $MPa^2 \cdot hr$
- B Risk of rupture
- b Width of MOR specimen, m
- h Height of MOR specimen, m
- K Constant, defined by Eqn. 10
- K_I Stress intensity $MPa/\sqrt{m}$
- K_{IC} Critical stress intensity, a material parameter, $MPa/\sqrt{m}$
- L_1 Bottom span of MOR specimen, m
- L_2 Top span of MOR specimen, m
- m Weibull Modulus
- MOR Modulus of rupture, MPa
- MOR_0 Characteristic modulus of rupture, MPa
- n Crack velocity exponent
- P_f Probability of failure
- R Reliability as a function of time
- R_{ff} Fast fracture reliability
- σ Stress, MPa
- σ_0 Characteristic strength of the structure, MPa
- σ_n Normal stress, MPa
- $\sigma_1, \sigma_2, \sigma_3$ Maximum principal stresses, MPa
- σ_0 Weibull parameter, $MPa/(m^3)^{1/m}$

t Time, hours
V Volume, m³
V Crack velocity, m/sec
Y Stress intensity factor coefficient, non-dimensional
 ψ Azimuthal angle
 ϕ Polar angle

TABLE I

Thermal Properties

	Temperature °C	Thermal Conductivity $\frac{\text{watt}}{\text{meter } ^\circ\text{C}}$	Specific Heat $\frac{\text{joule}}{\text{kg } ^\circ\text{C}}$
Hot Pressed Silicon	21.	29.4	754.
Nitride	260.	26.0	963.
Density = 3.19 gm/cm ³	538.	22.5	1088.
	816.	19.0	1214.
	1092.	15.9	1381.
	1371.	13.8	1340.

TABLE II

Elastic Properties

	Temp.	Young's Modulus	Poisson's Ratio	Shear Modulus	Coefficient of Thermal Expansion
	°C	GN/m ²		GN/m ²	1/°C
Hot Pressed Silicon Nitride					
Density	23.	320.	.280	122.	1.13
=3.19 gm/cm ³	600.	311.	.278	121.	3.39
	800.	308.	.277	120.	3.59
	1000.	301.	.275	118.	3.67
	1100.	297.	.274	116.	3.47
	1200.	287.	.276	112.	3.45
	1300.	274.	.276	108.	3.43
	1400.	257.	.274	101.	3.25

TABLE III

Fast Fracture Properties

Temperature °C	Characteristic MOR MPa	Weibull Modulus
20	733.	15.
900	568.	15.
1000	532.	15.
1100	480.	15.
1200	425.	15.
1250	373.	15.

Specimen Dimensions ("A"-size bar)

Width	6.350 mm
Height	3.175 mm
Inner span	9.525 mm
Outer span	19.050 mm

TABLE IV

Time Dependent Properties

Temperature	Parameter B	Crack Velocity Exponent
°C	MPa ² -Sec	
21	515.	40
1100	515.	40
1150	515.	40
1200	8.81	40
1250	.12	40

TABLE V

Forces Simulating Blade Loads

<u>Node Number</u>	<u>Force Newtons</u>
236	5148.8
237	12821.9
238	15903.6
240	15996.9
241	13617.0
242	5631.7

TABLE VI

Heat Transfer Data

	Element Number	Node 1	Node 2	Heat Transfer Coefficient $\frac{W}{m^2 \cdot K}$	Adiabatic Wall Temperature $^{\circ}C$
Pedestal	216	243	242	2650.	1250
	215	242	241	1480.	1250
	214	241	240	1260.	1250
	213	240	239	1230.	1250
	212	239	238	1200.	1250
	211	238	237	1180.	1250
	210	237	236	1150.	1250
	209	236	235	1130.	1250
Upstream	100	121	120	1170.	700
Face of Disc	99	120	119	1150.	701
	110	119	130	1090.	709
	118	130	137	1030.	712
	124	137	144	970.	722
	130	144	151	925.	730
	136	151	158	885.	737
	142	158	165	850.	745
	148	165	172	815.	750
	154	172	179	790.	757
	160	179	186	760.	763
	166	186	193	730.	772
	172	193	200	710.	776
	178	200	207	690.	795
	192	207	216	660.	820
	200	216	225	640.	900
	208	225	234	625.	1042
	216	234	243	608.	1150
Downstream	88	95	109	580.	755
Face of Disc	101	109	122	550.	757
	111	122	131	520.	763
	119	131	138	490.	776
	125	138	145	465.	786
	131	145	152	450.	795
	137	152	159	435.	800
	143	159	166	420.	810
	149	166	173	410.	815
	155	173	180	400.	825
	161	180	187	390.	835
	167	187	194	383.	845
	173	194	201	380.	900
	179	201	208	370.	995
	193	208	217	365.	1100
	201	217	226	355.	1230
	209	226	235	350.	1305

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