On the Reliability of Ceramic Turbocharger Rotors

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ABSTRACT

This paper describes reliability evaluation of ceramic turbocharger rotors. The analytical approache includes stress analysis by 3-D FEM, Weibull's probabilistic distribution function for brittle materials, lifetime prediction based on the slow crack growth mechanism. The bonding technique for joining ceramic rotor to metal shaft, the effect of the blade thickness on FOD, and the newly developed ceramic turbocharger rotor(CNR-1) with greater reliability and higher performance are also described. The accumulated number of passenger cars with a ceramic turbocharger in Japanese domestic market reaches more than 200,000, since 1985, the first year of introduction.

INTRODUCTION

Turbocharging has become a rather common means for increasing engine output since 1979, when the first passenger car equiped with a metalic turbocharger was introduced into market by NISSAN in Japan. Compared with a naturally aspirated engine of the same output, however, a turbocharged engine has a specific acceleration feeling, so-called 'turbo-lag'.

The utilization of ceramics instead of metals for turbocharger rotor offers the user improved rotational response which transrates directly into improved turbocharger boost response (reduction in 'turbo-lag'). NISSAN has successfully introduced a vehicle (domestic model of NISSAN 200Z) with a ceramic turbocharger into a commercial market in October 1985. Up to the present, NISSAN has put on the market two types of ceramic turbocharger, a first generation type(CN-1) and a second generation type(CNR-1). The accumulated number of passenger vehicles with these ceramic turbocharger is supposed to bemore than 200,000. This paper describes the outline of developing these two types of ceramic turbocharger rotors.

CERAMIC MATERIALS

In a turbocharger system for a passenger car, the gas temperature at the inlet of a turbine rotor is approximately 900 °C. The materials for the turbine rotor must meet the following requirements.

(1) mechanical strength

(2) thermal shock resistance

(3) oxidation resistance

(4) creep resistnce

(5) resistance to impact damage by foreign objects(FOD)

Ceramic materials that can meet these requirments include silicon nitride, sialon and silicon carbide. On selecting materials for a turbocharger rotor, a combination of the coefficients of thermal expantion and thermal conductivity, which influences on thermal strsses in the rotor, must be considered. Of these materials, silicon nitride is superior to the other materials in terms of the mechanical strength, dynamic strength and low thermal stress in both steady state and transient conditions

As for the sintering methods for densification of silicon nitride, normal sintering method(SSN) and gas pressure sintering method(GPSSN) were selected as the suitable techniques. Different sintering aids and their compositions were selected to the specific conditions for each sintering method.
The material properties of these two types of silicon nitride are slightly different as shown in the Table 1[3], but both materials fulfill the requirments of turbocharger rotors, and are now used in CNR-1.

MANUFACTURING CERAMIC ROTOR

Shaping techniques of a ceramic rotor include two types. The first, as described in Ref. 2, is the two piece technique, in which the blade is formed by injection molding and the hub is formed by cold isostatic pressing. The two preforms are then joined into one unit by cold isostatic pressing, and then gas pressure sintered(Fig.1)[2]. The second is based on a new shaping method where the blade and the shaft are formed simultaneously by injection molding.

BONDING TO THE METAL SHAFT

The bonding of a ceramic rotor to a metal shaft is one of the most critical issue that must be solved to achieve a practical ceramic turbocharger. Fig.2 shows the temperature distribution in a turbine rotor-shaft assembry during heat soak back condition[2]. Possible joining locations of the rotor and the shaft are at A,B and C. A or B may be most advantageous from the standpoint of thermal stress and easiness of the bond ing technique. However, in the case of failure at the joint (A or B), the shaft may be detached from the bearing system an d engine oil may flow out throuhg the exhaust system.In the worst case, it leads to a fire in the engine room.

From these reasons, C was selected as the joining face, where the temperture at the heat soak back is rather high. The ceramic rotor and the metal shaft exhibit large differences in their mechanical properties, especially in thermal expansion coefficient. In order to form a stable and reliable bond between them, a number of thchnical difficulties had to be overcome. After several investigations, two different types of bonding methods were selected, one is an active-brazing, and the other is a shrink-fitting. The feature of each bonding method is summerized below.

BRAZING BONDING---The design of brazing bonding method developed by NGK Spark Plug Co.is shown in Fig.3[3]. The silicon nitride rotor and metal shaft are bonded using an active brazing alloy containing titanium. Multi buffer layers of Ni and

W are located between the rotor and the shaft to reduce the residual thermal stresses which are generated by the difference in thermal expansion coefficient.

SHRINK FIT BONDING--The design of the shrink fit bonding method developed by NGK Insulators Ltd. is shown in Fig.4[3]. The ceramic shaft is clamped in two areas, the diameter of which are different from each other. Clamping at the larger diameter gives the rotor sufficient bending strength, while clamping at the smaller diameter gives it sufficient tortional strength.

Each type of bonding was subjected to various strength tests in order to confirm its reliability and durability under the actual use.

IMPROVEMENT OF FAILURE PROBABILITY

The metallic turbine rotor is made by precision casting of a high temperature super alloy. Fig.5 shows one example of stress distribution of the metal rotor at the maximum rate of revolution(Ref.1). The maximum stress is 85% of material yield stressat the blade front end area. Fig.6 shows the results of FEM analysis of a ceramic turbin rotor with the same geometry as the metallic one[1]. The stress distribution is almost the same as the metallic rotor. However, in this case, the maximum stress is 140% of the material tensile strength. Therefore, stress reduction and/or material strength improvement are necessary for reliable turbine rotors. Considering a brittle nature of ceramics, we should reduce stress levels and avoid stress concentrations in the rotor geometry design. This requires a more accurate stress analysis, and a 3-dimentional FEM has been used. According to the stress anarysis, the critical aeras in a rotor design can be summerized as follows. (See Fig.7)

(1)the taper from the back face to the shaft

(2)the connection area between the back face and shaft

(3)the distribution of thickness of the blade from tip to root

(4)the shape of the hub on the exducer side

The stress distribution of an example of a ceramic rotor with optimized shape is shown in Fig.8[(2)]. This shows the combined stress from centrifugal and thermal stresses under the condition of tip speed of 590 m/s and the turbine inlet temperature of 900°C. In this example, the maximum stress was reduced by more than 20%, without any loss in aerodynamic performance. Details of the approach employed to reduce the stress of the CN-1 type rotor is reported in Ref.2.

The purpose of developing CNR-1 type rotor was for further improvement in accelerating response and reliability. Thedifferences in geometries of the two rotors are shown in Fig.9[(4] The main modifications made in CNR-1 rotor are as follows:

(1)the rotor diameter was reduced by approximately 10% so as to lower the moment of inertia

(2)the thickness of the blade tip was increased by 50% so as to increase the resistance to FOD(foreign object damage)

(3)the blade thickness distribution and the contour between the back face and shaft were optimized to reduce stresses

As shown in Fig.10[4] and Table 2, the design stress of the CNR-1 rotor is reduced by approximately 15%. Average fracture strength in the hot spintest of CNR-1 and CN-1 rotor is shown in Table 2.[4] Both rotors have almost the same strength as 353MPa for the CN-1 and 367 MPa for the CNR-1, respectively. However, the ratio of the average fracture strength to the design stress of CNR-1 rotor is 2.94, greater than that of CN-1 of2.40. This lower stress design makes the CNR-1 rotor much more reliable.

LIFETIME PREDICTION

Not only metallic but also ceramic turbochargers for passenger cars are expected to last for at least 10years without any failure. The prediction of the lifetime is essential in the development of high reliable ceramic turbine rotor.

Under the actual condition of turbocharger rotor, slow crack growth is thought to be a dominant mechanism of failure of the rotor. The slow crack growth velocity in a ceramic materialis shown by the following equation.

$$v = da/dt = A*K_I^N \qquad (1)$$

where

a: crack length

t: time

A,N: parameters for slow crack growth

K_I: stress intencity factor

K_I is expressed as follows.

$K_I = Y * \sigma * a$ --------------------------(2)

where

Y: shape factor

σ: stress

From Eqs. (1) and (2), the life time of a ceramic material can be expressed by the next equation,

$t_c = a_i^{(2-N)/2} / (I * \sigma^N)$ ------------------(3)

where

$I = (N-2) * A * Y^N / 2$ -----------------------(4)

a_i: initial crack length

This shows that the lifetime of ceramic material depends on the initial crack length, applied stress and parameters A and N. In order to predict the lifetime, A and N values under the actual condition must be known. These values were determined experimentally by the hot spin test of ceramic turbocharger rotors at a temperature of 900°C and a constant speedof 650 m/s. Fig.11[4] shows the relation between survival probability and the lifetime of tested rotors. In this test, values of N=30 and $A = 2.34 * 10^{-33}$ were obtained.

Using these values of A and N, the relationship between lifetime and failure probability of CN-1 and CNR-1 rotor can be calculated as shown in Fig.12[4]. The failure probability of the lower stressed CNR-1 rotor after 1000 hrs of operation is predicted to be $1/10^7$, compared to CN-1 of $1/10^6$.

In order to achieve higher levels of reliability, proof testing is effective. Fig.13[2] shows the results of constant speed endurance test of the survived rotors in the proof testing. The solid line shows the predicted minimum lifetime, and every rotor has a longer lifetime than this predicted minimum lifetime, which shows that the predicting method of lifetime based on the values of A and N obtained from the rotor hot spin test is rather reasonable, and that the proof test is very effective for guaranteeing the lifetime of ceramic rotor.

IMPROVING STRENGTH AGAINST FOD

During the early stage of hot spin test of ceramic rotors, we often experienced that some rotors burst at an extremely low rotational speed than expected. Analysing the test data, we concluded that the rotors were impacted by oxidized metal scales, metal fragments and other particles coming from the upstream of the test apparatus, and that a filter must be equipped at the turbine inlet as shown in Fig. 14(Ref.2). Because ceramics are more brittle than metals, it is very important to have a good understanding of the phenomena that occur when foreign objects impact ceramic rotors. After several analytical and expermental investigations, it was found that impacts by foreign objects were concentrated on the tip of the blades. From the results of some analysis on the dynamic stress when a particle hits the tip of a blade, it was expected that increasing the brade thickness would resist to damage by particles impact(FOD:foreign objects damage).

Fig.15[4] shows the relationship between blade tip thickness and the critical weight of particles (small steel balls) in the impact test of CN-1 rotor. When the weight of the particles were below the critical value, there was not any sign of FOD on ceramic rotors. As shown in Fig.15, it is clear that an increase in the blade tip thickness is effective to improve the FOD resistance. However, an increase in blade thickness produces an incrase in centrifugal stress in the rotor. In CNR-1 rotors, the blade tip thickness was increased by approximatelly 50%, but the stress level was lower than that of CN-1 rotors by contour optimization treatment on the blade roots.

SUMMARY

With the aim of improving the acceleration response of turbocharged passenger cars, development of ceramic turbine rotor has been carried out. The results are summarized;

(1) Sintered silicon nitride and gas pressure sintered silicon nitride were found to be the most suitable materials for ceramic turbocharger rotors.

(2) Both the active-brazing involving the formation of a metallized reaction layer and shrink-fitting provided sufficient reliability for joining the silicon nitride rotor and

metal shaft.

(3) Carefully designed ceramic rotor is highly reliable. (more than 200,000 passenger cars with a ceramic turbocharger have been introduced in market without any serious problems)

(4) Increasing blade tip thickness is an effective way to improve the strength of ceramic rotors against FOD.

REFFERECES

(1) Y.Okazaki, N.Matsudaira, M.Matsuda: 'Ceramic Turbine Wheel Developments for Mitsubishi Turbocharger', SAE Technical Paper 850312, pp25, (1985)

(2) K.Katayama, T.Watanabe, K.Matoba, N.Katoh: 'Development of Nissan High Response Ceramic Turbocharger Rotor', SAE Technical Paper 861128, (1986)

(3) K.Matoba, K.Katayama, M.Kawamura, T.Mizuno: 'The Development of Second Generation Ceramic Turbocharger Rotor-Further Improvements in Reliability', SAE Technical Paper 880702, (1988)

(4) K.Katayama, M.Sasaki, T.Itoh: 'Development of Ceramic Turbine Rotors', ASME Paper 88-GT-282, (1988)

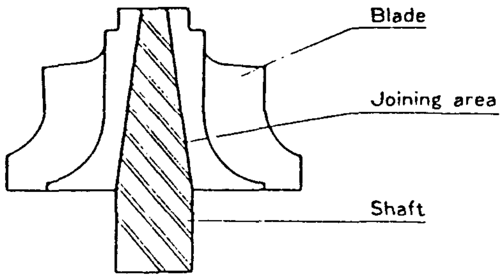


Fig. 1 Ceramic rotor from two-piece-preform

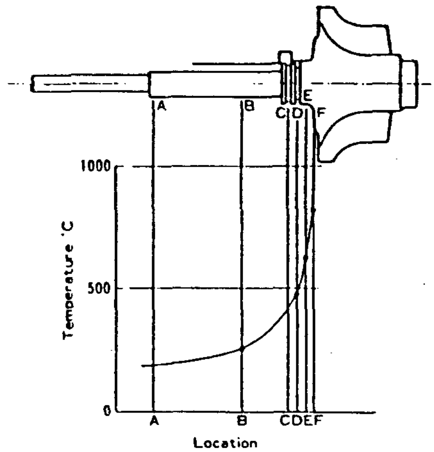


Fig. 2 Temperature distribution in turbine rotor shaft dering heat soak back

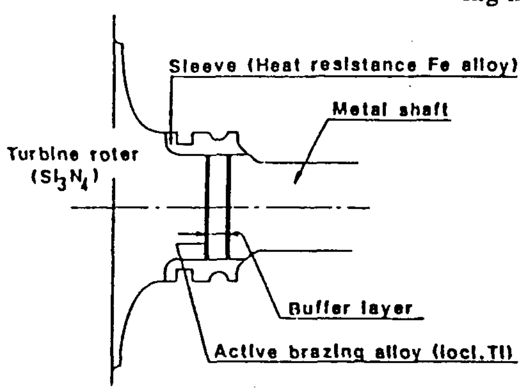


Fig. 3 Design of bonding method (active-brazing)

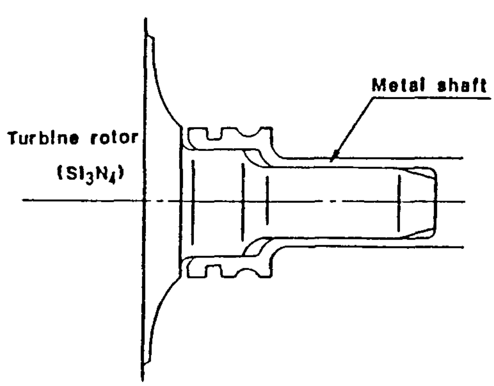
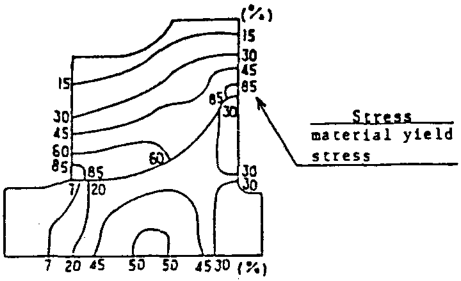


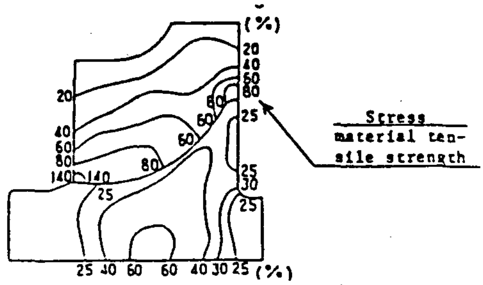
Fig. 4 Design of bonding method (shrink-fitting)



Material : INCO 713C
(Nickel base alloy)

Rotational speed: 145,000 RPM

Fig. 5 Stress distribution in a metal rotor



Material : Ordinary Silicon Nitride (Si_3N_4)

Rotational speed: 145,000 RPM

Form : Same as metal wheel

Fig. 6 Stress distribution in a ceramic rotor

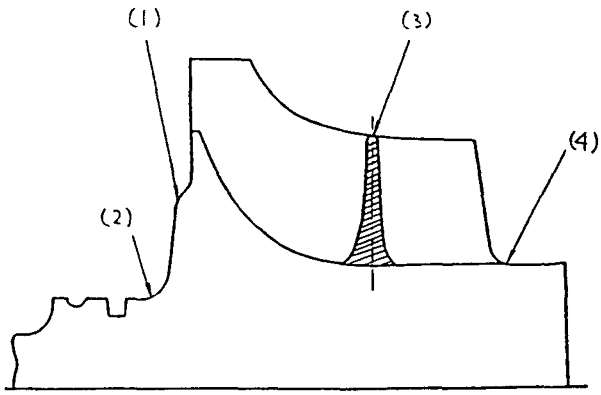


Fig. 7 Critical areas in rotor designing

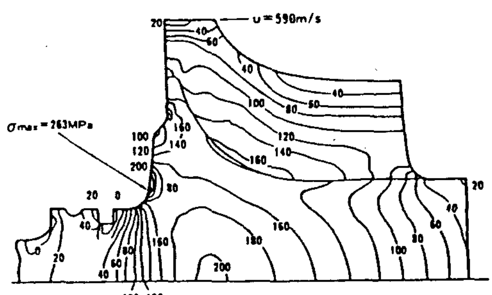


Fig. 8 Combined stress distribution in a ceramic rotor

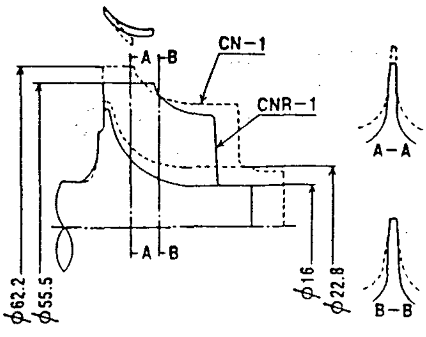


Fig. 9 Comparison of CNR-1 and CN-1 rotor geometry

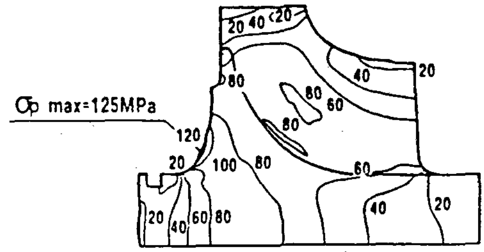


Fig. 10 Combined stress in CNR-1 rotor

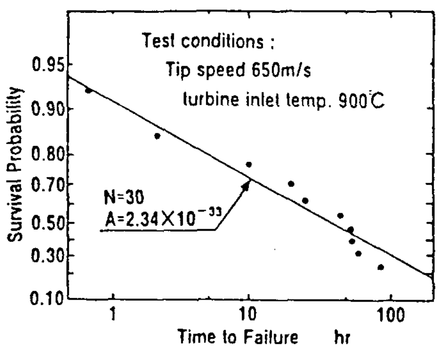


Fig. 11 Relationship between survival probability and lifetime

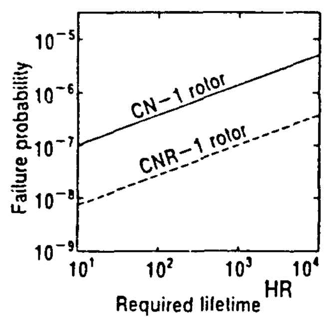


Fig. 12 Relationship between failure probability and required lifetime

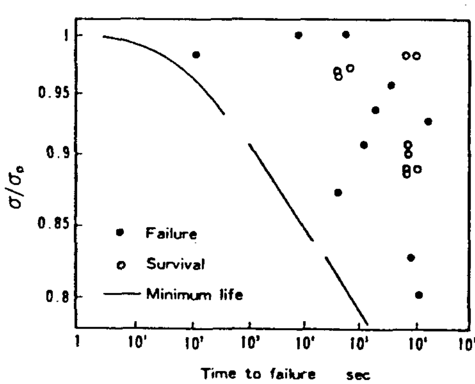


Fig. 13 Lifetime after proof testing

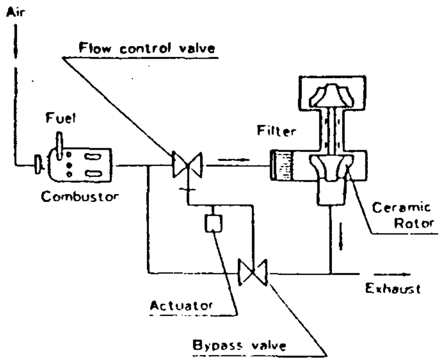


Fig. 14 Test equipment

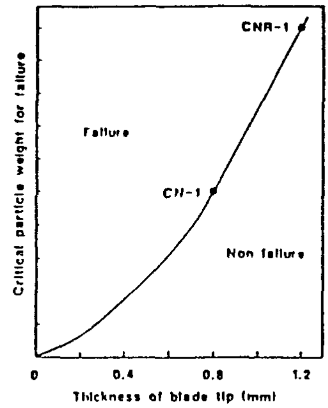


Fig. 15 Effects of thickness of blade tip on FOD

		Silicon Nitride	
		Normal Sintering	Gas Pressure Sintering
Specific gravity (g/cm^3)		3.15	3.27
Young's modulus (GPa)		250	310
Poison's ratio		0.25	0.24
Thermal conductivity (cal/cm·sec·°C)		0.08	0.07
Thermal expansion coefficient (10^{-6}/°C)		3.4	2.8
Critical stress intensity factor (MN/m$^{3/2}$)		6.8 (Chevron notch)	6.4 (Indentation)
Thermal shock resistance* (°C)		900 (3×4×40)	570 (4×8×30)
Flexural strength** (MPa)	R.T.	800	900
	800°C	800	850
	900°C	580	—
	1000°C	—	740
Oxidation weight gain (mg/cm^2)		0.06 (900°C-100Hr)	0.01 (1000°C-100Hr)
Creep properties		No sign at 900°C	No sign at 800°C

* Test piece temperature which crack occur upon immersion into 0°C water.
** 3-point bending ,test bars cut from rotor.

Table 1 Materials properties of ceramic turbocharger rotor

Type	CN-1	CNR-1
Ave. fracture strength, MPa	353	367
Ave. tip speed, m/s	701	723
Weibull modulus	16	18
Design stress, MPa	147	125

Table 2 Test results in CNR-1 and CN-1