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SILICON NITRIDE COMPONENTS FOR AGATA - A EUROPEAN GAS TURBINE FOR HYBRID VEHICLES

Robert Lundberg,
Volvo Aero Corporation
Trollhättan, Sweden

Jan Adlerborn
AC Cerama AB
Robertsfors, Sweden

ABSTRACT

The European EUREKA project, EU 209, otherwise known as AGATA (Advanced Gas Turbine for Automobiles), is a programme dedicated to the development of three critical ceramic components - a catalytic combustor, a radial turbine wheel and a static heat exchanger - for a 60 kW turbogenerator in an hybrid electric vehicle. These three components, which are of critical importance to the achievement of low emissions and high efficiency, will be designed, developed, manufactured and tested as part of a full scale feasibility study. AGATA is a joint project conducted by eight commercial companies and four research institutes in France and Sweden. Silicon nitride ceramics play an important role both in the development of the catalytic combustor and for the radial turbine wheel. This paper outlines the main results of the AGATA project with special emphasis to the development of Si_3N_4 combustor and turbine wheel.

INTRODUCTION

The goal of the AGATA project is to develop three critical ceramic components - a catalytic combustor, a radial turbine wheel and a static heat exchanger - as part of a full scale feasibility study, with a view to the eventual application of the concept in the automotive industry. As well as automakers, the participants in AGATA represent companies and research institutes in the turbine, catalytic materials and ceramics fields in France and Sweden. The AGATA project has been outlined in three previous papers[1,2,3], and in a separate paper at this conference[8]

BACKGROUND

The gas turbine has been considered an alternative automotive power source since the 1950s, its advantages including low weight and the ability to run on different fuels. The unit's main drawback is its low efficiency at low loads. If a gas turbine is run continuously at high load, its efficiency will be high and the exhaust emissions low. This is the case in an hybrid electric vehicle, in which the electric motor is used to drive the car and the gas turbine operates at a high, constant load to charge the batteries. Hybrid drive systems of this type are undergoing trials in the threeVolvo Environmental Concept Vehicles (a passenger car, a truck and a bus).

The gas turbines used in these vehicles are built from metallic components and metallic, low-emission combustors of the lean premix, prevaporisation type are also installed. The efficiency of a gas turbine can be improved considerably by increasing the turbine inlet temperature. This value can be raised to 1350°C using a ceramic turbine wheel, the resultant increase in efficiency yielding a 20% reduction in fuel consumption.

The combustion temperature must be lowered to reduce the NO_x emissions. Combustion can be maintained at a value as low as 1350°C, with a dramatic reduction in NO_x , when a catalytic combustor is used. In practice this means that both the combustion chamber and combustor honeycomb substrate must be made of ceramic materials capable of operating at this temperature without cooling. Thus, the advent of ceramic components represents a major step towards the achievement of higher efficiencies and lower exhaust emission levels, making the gas turbine an even more attractive potential power source for hybrid vehicles.

OBJECTIVES OF AGATA

As conceived in 1987, the original aim of the AGATA project was to develop a 100 kW gas turbine to drive a conventional car power train. However, since the use of a gas turbine in an hybrid electric vehicle offers further advantages in the automotive context, the AGATA project was redefined to take account of these in 1992, while the turbine industry is also showing an interest in small turbogenerators for use as clean, high efficiency auxiliary power units (APUs) in aircraft applications. With a total budget of 120 million French Francs, the revised AGATA project commenced early in 1993 and will occupy a four-year period until the end of 1996.

The purpose of the AGATA project is to develop and test the foregoing three components as part of a full-scale feasibility study of a unit with the following specifications:

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Table 1.

Mechanical output	60 kW
Specific fuel consumption	200 g/kWh
Turbine inlet temperature	1350°C
Emission standard	ULEV or equivalent European standard
Fuel	Diesel oil or alternative fuel
Application	Hybrid electric vehicle

CATALYTIC COMBUSTOR

The best technology available today in the area of low NO_x emission combustors for small gas turbines is based on the lean premix, prevaporisation (LPP) concept. A catalytic combustor provides an attractive, alternative means of achieving even leaner air/fuel mixtures and lower combustion temperatures, with the aim of further reducing thermal NO_x emissions. The field of high-temperature materials for catalytic combustion has recently been reviewed[4] and the concept of the catalytic combustor will be developed further as part of the redefined AGATA project.

The catalytic combustor arrangement incorporates a start-up preheater. Since preparation of the air/fuel mixture is based on the LPP concept, the catalytic combustor represents a logical evolution of existing technology in that area. A preliminary combustor configuration used for laboratory testing is shown in Fig. 1.

The main emphasis of the technical development programme is on ceramic structural components and catalytic combustion. All of the ceramic components - principally the combustor housing, honeycomb substrate and afterburner - will operate without cooling at 1350°C. The housing and afterburner are manufactured respectively by Aerospatiale, France, and AC Cerama, Sweden, from high-strength, thermal shock resistant, high-performance Si_3N_4 ceramics with proven potential for long-term operation at 1350°C. The housing of the catalytic section is made of SiC-whisker-reinforced Si_3N_4 rings by Aerospatiale. Whisker reinforcement increases thermal shock resistance, toughness and creep resistance. The rings are manufactured by uniaxial hot pressing. The exit cone is manufactured by AC Cerama using glass encapsulation and HIP (Hot Isostatic Pressing). The Si_3N_4 ceramic afterburner cone is shown in Fig. 2. The rings and cone are joined by polished conical contact surfaces and the combustor is held together by externally mounted springs.

The combustor honeycomb substrate must also be designed for operation at 1350°C. The substrate used in automotive catalytic converters is a ceramic honeycomb structure of extruded cordierite ($2MgO{\cdot}2Al_2O_3 \cdot 5SiO_2$). Since the melting point of cordierite is approx. 1450°C, operation at 1350°C is open to question. At present, other ceramic honeycomb substrates (both oxides and non-oxides)with better high-temperature properties are under study as part of the AGATA project, so far with promising results.

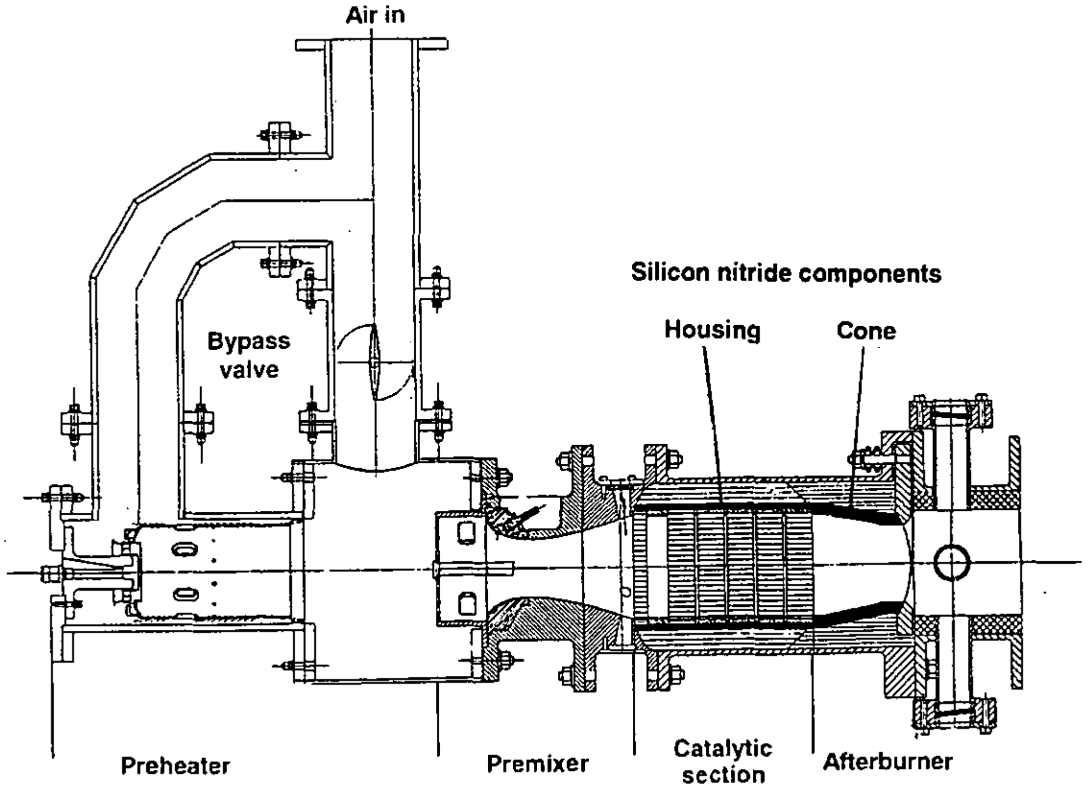

Fig. 1 Preliminary laboratory lay-out of full-scale catalytic combustor.

Considerable progress has been made in identifying a suitable catalyst offering high activity, low light-off temperature and good thermal stability. Candidate catalysts have been selected after an accelerated ageing at 1350°C in flowing moist air (1,5 % H_2O), in a screening test. The best catalysts from this screening test have been selected and are currently being tested in a pilot scale catalytic combustor rig. A more detailed description of the catalytic combustor is presented elserwhere[2,8]. A full scale catalytic combustor will be tested under realistic gas turbine conditions - both transient and steady state - at a later stage of the project, using optical laser diagnostics to verify the emission values.

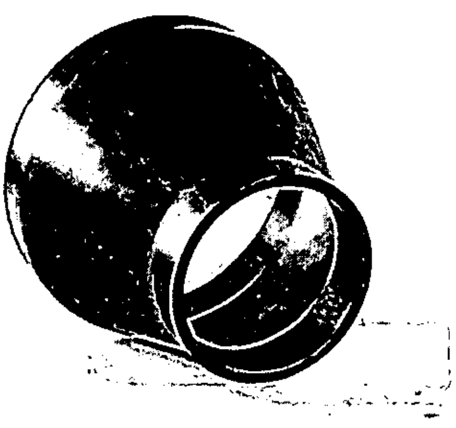

Fig. 2 Ceramic combustor exit cone made by AC Cerama, CSN 101 grade, HIPed Si_3N_4

TURBINE WHEEL

The objective of this sub-project is to establish fruitful cooperation between designers and ceramic manufacturers, generating a beneficial influence on design and material development activities. Interaction of this nature is of the utmost importance in designing and manufacturing a ceramic turbine wheel capable of operating at a high rotational speed and a turbine inlet temperature of 1350°C. Two different ceramic processing techniques are undergoing evaluation, Si_3N_4 being the material in each case. AC Cerama AB, Sweden, is developing a method of combining two green-forming (or powder-forming) methods with their proprietary glass encapsulation and hot isostatic pressing (HIP) technique[5]. Céramiques & Composites, France, will manufacture the wheel by injection moulding as a single piece, using gas pressure sintering (GPS) to produce a dense, extremely tough Si_3N_4 material.

The design of the wheel (the latest version of which is shown in Fig. 3.) is the responsibility of Volvo Aero Turbines, a subsidiary of Volvo Aero Corporation, which specialises in small gas turbines. The rotor has been designed with a fairly high tip speed. The overall geometry and blade thickness distribution have been selected in cooperation with the ceramic manufacturers. Efforts have been put into reduction of surface stresses at the blade roots.

Thorough stress analyses, both transient and steady state, have been carried out for several design iterations. Maximum stress, which is below 300 MPa, occurs during the cold start transient. Weibull statistics have also been included in the FEM programme and failure probability has been calculated. Life time calculations based on tensile creep experiments will be performed.

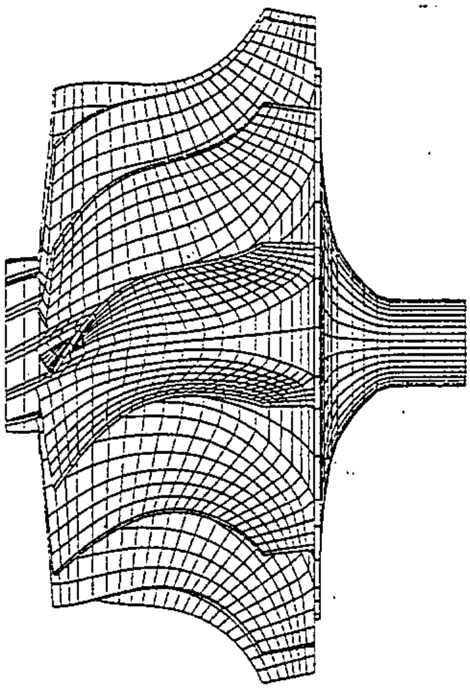

Fig. 3 Finite element model of AGATA ceramic turbine wheel.

The ceramic wheel will be joined to the metal shaft by brazing. A two-step brazing process has been developed by CEA/CEREM, France, in which the ceramic surface is first metallised and then brazed to the metal shaft. Another important technique that is being developed in the AGATA project is non-destructive inspection both of the ceramic to metal joint and of the ceramic wheel itself.

Both spin discs and wheels of the final design will be cold-spin burst-tested. Hot-spin testing will be performed in a gas turbine rig under actual pressure, temperature and aerodynamic loading conditions. These tests will take the form of start/stop, low-cycle fatigue tests. Spin discs have already been manufactured (see Fig. 4) and will be cold spin tested starting December 1995. The hot spin tests are scheduled for 1996.

HEAT EXCHANGER

A recuperative, fixed geometry heat exchanger with a target efficiency of 90 % has been chosen for AGATA. Two basic types - plate and tubular - are under study. The Céramiques & Composites company has long experience of green forming by extrusion and of other forming methods used to produce sintered silicon carbide and cordierite ceramics. Green forming techniques have been developed further within the framework of the project in order to produce extremely thin-walled components, while ceramic-to-ceramic and ceramic-to-metal bonding techniques for heat exchanger assembly represent another major aspect of the research work.

Ceramic prototypes have already been produced and the feasibility of full-scale production has been demonstrated. The plate concept is based on assembling successive layers of undulated (wavy) profiles separated by thin flat sheets. Due to the high thermal efficiency required and the volume constraints, a counter flow design has been adopted. More details about the heat exchanger is presented elsewhere[2,8]. Full-scale testing of the heat exchanger will be performed during 1996.

HIPed SILICON NITRIDE COMPONENTS

To meet the demands of high strength and fracture toughness coupled with good creep resistance at 1350°C and good thermal shock resistance AC Cerama AB, Sweden, has developed the Si_3N_4 grade CSN 101. This material, containing high purity Si_3N_4 powder with 3 wt% Y_2O_3 as sintering aid, can be green formed either by injection moulding or by cold pressing. The densification is then performed using the proprietary glass encapsulation and hot isostatic pressing (HIP) technique[5,6].

For the AGATA project the CSN 101 Si_3N_4 has been chosen for the conical afterburner section of the catalytic combustor (see lay-out in Fig. 1.). This component is manufactured at the prototype scale by cold isostatic pressing, followed by green machining, glass encapsulation and HIP. In a future larger production volume such a piece could be formed by injection moulding. The outer and inner surfaces of the combustor component will be used with as-HIPed surface finish. Only the contact surfaces are machined after HIP. A prototype afterburner cone (full size) is shown in Fig. 2.

The CSN 101 Si_3N_4 is also one of two candidate Si_3N_4 materials investigated for the radial turbine wheel. AC Cerama has developed a technique of combining two green-forming methods in a two-piece approach. The hub section of the wheel is formed by cold isostatic pressing (CIP) and green machining, while the blade-ring is injection moulded. Following binder burn-out, the hub and blade ring are green-joined, glass encapsulated and HIPed, the advantage being that binder burn-out is achieved much more quickly and easily with two smaller components, than when the component is injection moulded in a single piece. Full scale spin discs have already been produced using this two-piece approach (see Fig. 4).

Mechanical properties of the CSN 101 Si_3N_4 are currently being evaluated. 4-point flexure tests with a span of 40/20 mm on machined testbars of CIP+HIPed material from room temperature to 1350°C are presented in Fig. 5. The Weibull modulus at room temperature was found to be as high as m=28. 4-point flexural Stepped-Temperature-Stress-Rupture (STSR) tests going from 1000°C, 24 h in steps of 100°C (24 h at each temperature) up to 1400°C has also been performed. Both machined testbars and testbars with as-HIPed surface survived all the test up to >24 h at 1400°C with a 250 MPa load. At 300 MPa the samples with machined surface survived >24 h at 1400°C, while the samples with as-HIPed surface failed after a few hours at 1400°C. When a 350 MPa load was used all samples (machined surface or as-HIPed surface) survived the 1300°C period but failed after a few hours at 1400°C.

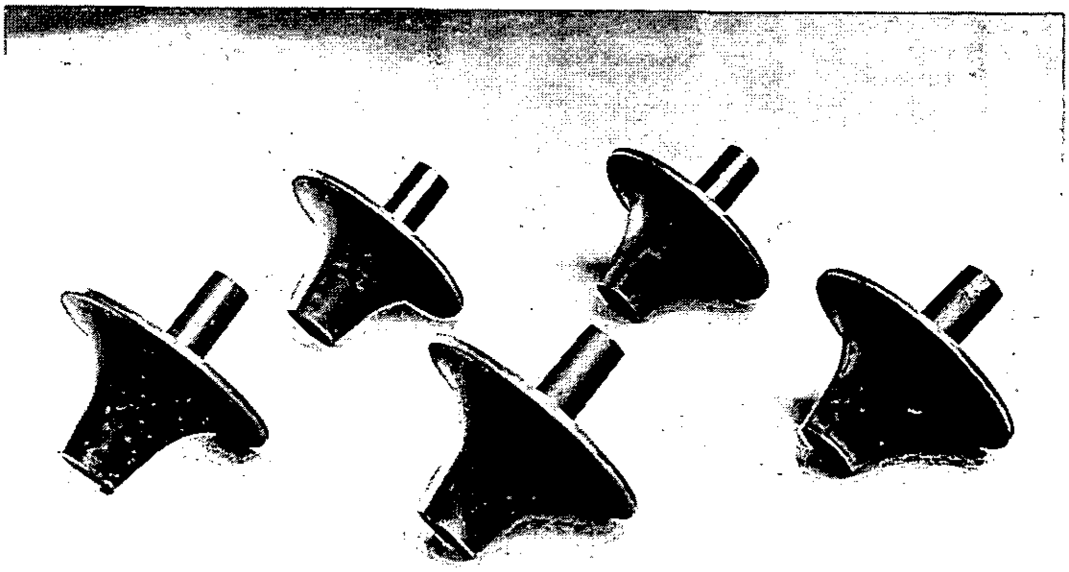

Fig. 4. Full scale spin discs made by AC Cerama, CSN 101 grade, HIPed Si_3N_4

These results are at the level of the best STSR results reported for Si_3N_4 materials[7]. An extensive tensile creep testing program has been recently started within the project. The first specimen has so far survived more than 1200 h at 1350°C, 50 MPa tensile stress. These results indicate that the CSN 101 is a good candidate for high temperature gas turbine applications. The good room temperature strength and relatively high fracture toughness (6 MPa$\sqrt{m}$, by the Chevron notch method) coupled with the ability to produce complex shapes at a low cost using injection moulding makes it an interesting material also for other applications.

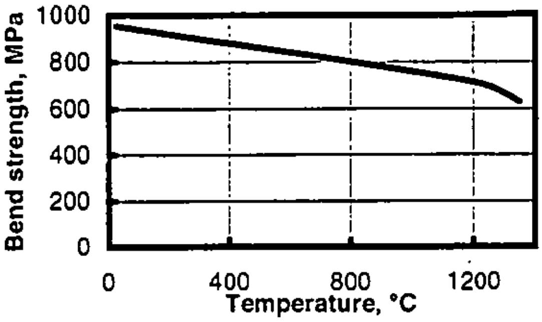

Fig. 5 4-point flexural strength of AC Cerama CSN 101 HIPed Si_3N_4 (m = 28 at room temp.).

Table 2. Properties of AC Cerama CSN 101 Si_3N_4.

Density	3.22 g/cm^3
Hardness	19 GPa
Flexural strength, RT 4-p	955 MPa
Weibull Modulus, RT	28
Flexural strength, 1350°C 4-p	630 MPa
Fracture toughness	6 MPa$\sqrt{m}$
Thermal expansion coeff.	$3.7 \cdot 10^{-6}$ K^{-1} (20-800°C)
Thermal conductivity, RT	40 W/mK

CONCLUSIONS

The first two years of the redefined AGATA project has yielded results in the areas of design, simulation, materials development, material properties and prototype production. All three sub-projects are on schedule to date and full-scale feasibility testing to verify the target technical specifications appears to be achievable. AC Cerama CSN 101 HIPed Si_3N_4 has been selected for the catalytic combustor afterburner and is a strong candidate for the radial turbine wheel. Mechanical properties of the CSN 101 Si_3N_4 have been found to be at the level of the best available high temperature Si_3N_4 materials.

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