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Authors:
R.A. Wenglarz
S.M. Calcuttawala
J.E. Pope

Contractor:
Allison Engine Company
P.O. Box 420
Indianapolis, IN 46206-0420

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CERAMIC VANE DEMONSTRATION IN AN INDUSTRIAL TURBINE

Richard A. Wenglarz
Satish M. Calcuttawala
J. Edward Pope

Allison Engine Company
P.O. Box 420
Indianapolis, IN 46206-0420

ABSTRACT

A U. S. Department of Energy (DOE) program with the Allison Engine Company will demonstrate ceramic vanes in an industrial turbine. First-stage ceramic vanes and their metallic mounts are to be designed, fabricated, and operated in a relatively short-term engine test (up to 50 hr). The ceramic vanes and mounts will then be retrofitted into an existing turbine for operation at a commercial site for an extended duration test (up to 8000 hr). The ceramic vanes and metallic mounts have been designed. Thermal and stress analyses of the vanes have calculated acceptable fast fracture stress levels and probabilities of survival exceeding 99.99% for turbine continuous power and emergency shutdown (thermal shock) conditions. The maximum calculated steady-state stress is 169 MPa (24.5 ksi) at a material temperature of 1182°C (2160°F). Consequently, currently available ceramics appear to provide acceptable fast fracture strengths for use in industrial turbines. Long-term materials tests will evaluate the life times and retained strength of ceramics at stress and temperature levels in the range calculated from the ceramic vane analyses. The results of these tests will support the decision on which vane material will be used in the long duration turbine demonstration. A successful demonstration could provide a basis for incorporating first-stage ceramic vanes into current generation industrial turbines and also the introduction of ceramic airfoils into downstream rows of future high temperature Advanced Turbine System (ATS) engines.

INTRODUCTION

A U.S. Department of Energy (DOE) program is being conducted to retrofit first-stage ceramic vanes into an Allison Model 501-K industrial turbine and demonstrate that engine for an extended duration at a commercial site. Another DOE/Solar Turbines, Inc., program (van Roode, et al., 1994, 1995, 1996) has a similar goal to demonstrate first-stage ceramic vanes in addition to ceramic first-stage rotor blades and ceramic combustor liners. Efforts for the DOE/Allison program include the following:

- design and analyses of ceramic vanes and mounting hardware
- ceramic vane procurement and mount fabrication
- thermal shock proof tests of the ceramic vanes
- proof tests of vanes and mounting hardware in a test engine
- demonstration of the ceramic vanes and mounting hardware in a long-term (up to 8000 hr) turbine run at a commercial site

A successful demonstration could provide a basis for incorporating first-stage ceramic vanes into current generation industrial turbines and also the introduction of ceramic airfoils into downstream rows of future high temperature Advanced Turbine Systems (ATS) engines.

As previously described (Wenglarz, et al., 1996), 2-D thermal and stress analyses evaluated ceramic first-stage vanes with the current shape in the Model 501-K turbine and with alternate shapes. Thermal shock conditions resulting from emergency shutdown due to loss of generator load were represented. These conditions are expected to produce the highest turbine vane stresses. Unacceptable stresses were calculated for a solid ceramic vane with the same shape as the metallic first vanes in the Model 501 turbine. That vane would experience high thermally-induced stresses during emergency shutdown because the thin trailing edge cools much faster than the thickest regions of the airfoil. Additional analyses showed that hollow construction would reduce thermal shock stresses by producing a more uniform thermal mass along the vane chord. However, discussions with ceramic suppliers indicated that only a small hollow region with little thermal shock benefit could be produced at a competitive cost in production quantities for vanes of the scale of the Model 501 turbine.

Consequently, the current Model 501 turbine vane shape could not be used for the retrofit, and a new, thinner airfoil was designed. The ratio of maximum thickness to trailing edge thickness was reduced to 4.3 for the new airfoil shape as compared to a ratio of 6 for the current metallic airfoil in the Model 501 turbine. A 2-D analyses calculated acceptable thermal shock probabilities of survival > 99.9% for the new airfoil shape (Wenglarz, et al., 1996). The aerodynamic performance of the new profile is also somewhat improved over that for the current Model 501 metal vane profile, which was developed years ago with less advanced aerodynamic analyses capabilities.

Having determined the airfoil shape using 2-D analyses, various vane platform and mounting designs were evaluated and reviewed with ceramic suppliers for their inputs on design features that affect production costs. An initial design was developed that decreases contact stresses and production costs. The vane is not hard mounted, and the contact area at metallic interfaces is minimized to reduce the extent of expensive diamond machining required for those interface surfaces.

This paper discusses the results of 3-D thermal and fast fracture stress analyses of the ceramic vane design in addition to long-term stress rupture considerations.

Vane Design and 3-D Fast Fracture Analysis

Figure 1 illustrates the ceramic vane and mount design and the finite element mesh network used for the 3-D ceramic vane analyses. About 7350 tetrahedron elements were used in the thermal and stress analyses of the ceramic vane by the Allison STRATA computer code. The ceramic vane consists of an airfoil with simple platforms bounding the inner and outer flow passage surfaces. The inner and outer platforms of the ceramic vane seat in the circumferential grooves of inner and outer metallic mounts. The ceramic vane can be distinguished from the metallic mounts by comparison of Fig. 1 with Figs. 5 or 6.

Stress Conditions

The most significant source of vane steady-state stress results from thermal gradients of the combustor temperature pattern. Ten vanes are located at the exit of the transition section from each of six combustors in the Model 501 turbine. Each vane experiences a different portion of the combustor temperature pattern and each combustor produces a somewhat different pattern. Three bounding temperature patterns were determined for the purpose of thermal and stress analyses from thermocouple data in Model 501-K engine tests. These bounding contours (shown in Fig. 2) result from radial planar cuts through the engine axis and measured combustor patterns at circumferential locations that produce the maximum inner gradient (MIG), maximum temperature (MT), and maximum outer gradient (MOG). The highest stresses are associated with the most severe gradients, and the lowest material strength is associated with the highest temperature.

The most severe stresses in the ceramic vanes result from thermal shock temperature gradients caused by the emergency shutdown. Figure 3 shows calculated temperature traces versus time after an emergency shutdown at two locations on the ceramic vane for the bounding combustor pattern with the maximum inner gradient. The two locations on the vane are at about one-half the vane chord and at the trailing edge, both in the midspan plane. Figure 3 shows that the thicker midchord region of the airfoil cools at a slower rate than the thin trailing edge during the emergency shutdown.

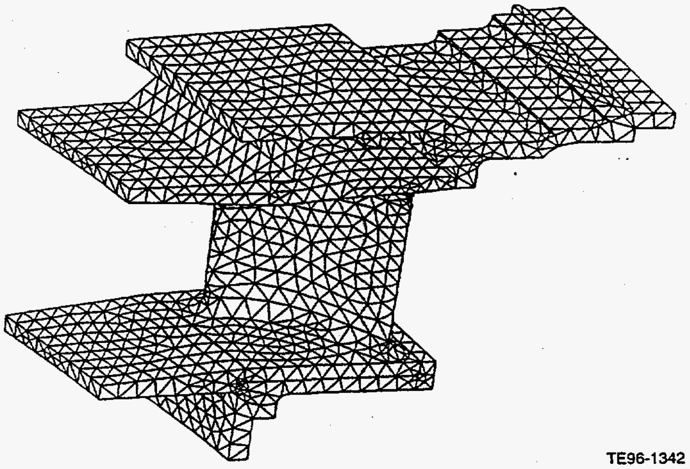
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Figure 1. Finite element mesh.

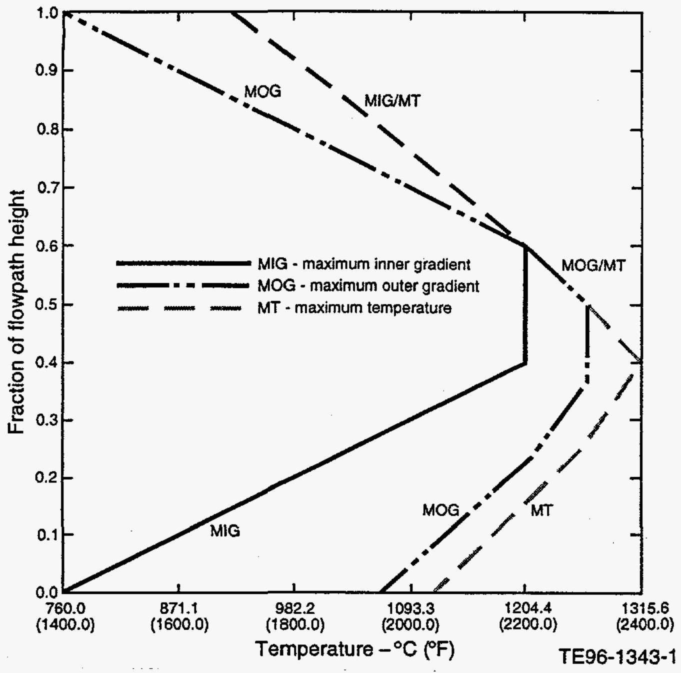

Figure 2. Bounding combustor radial patterns.

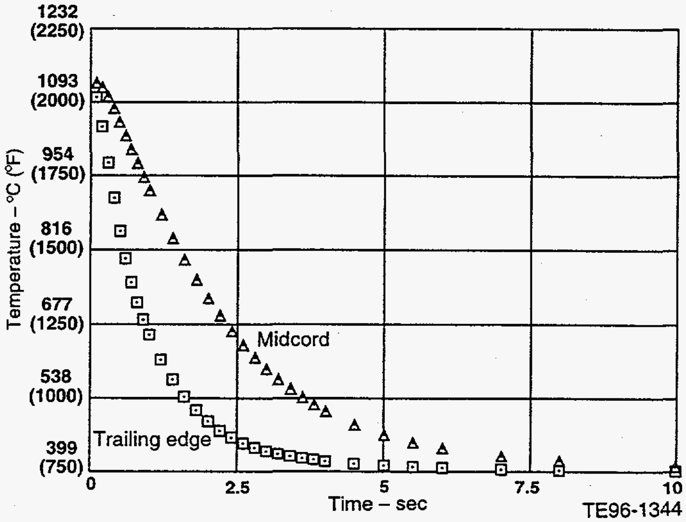

Figure 3. Vane temperatures at midchord and trailing edge due to emergency shutdown.

Figure 4 shows that the difference in temperature between the midchord and trailing edge locations reaches a maximum value of about -278°C (-500°F) at about 1 sec after the initiation of emergency shutdown.

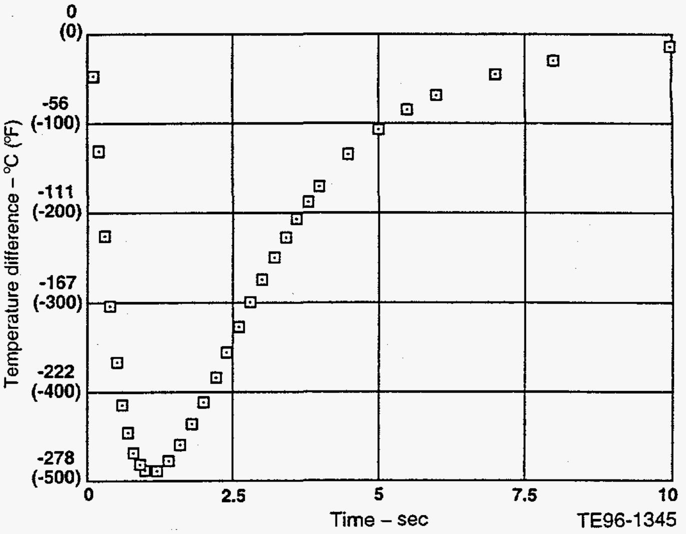

Figure 4. Vane temperature differential between trailing edge and midchord due to emergency shutdown.

3-D Analyses Results

All maximum continuous power and emergency shutdown stress analyses have been completed for the ceramic vanes using the three bounding combustor temperature patterns and AS800 Si_3N_4 material properties. Calculated ceramic vane fast fracture stress levels and probability of survival values have been acceptable for all of these cases. Tables I and II show results of the stress analyses. Maximum stresses in the vane are given for each condition along with the location of maximum stress, the material temperature at that location, and the probability of survival of all 60 vanes considering the statistical nature of the ceramic properties.

Figure 5 shows the thermal shock stress contours for the maximum inner gradient bounding combustor temperature pattern at about 0.9 sec after initiation of emergency shutdown. These conditions produce the highest calculated stress (208 MPa/30.2 ksi) of all the conditions evaluated. This stress, as well as maximum stresses for all the transient and steady-state analyses, occurs at the trailing edge of the ceramic vane in the region of midspan. Because the vane is experiencing rapid cooling in the emergency shutdown cases, the material temperature is relatively low. At the location of the highest (208 MPa/30.2 ksi) stress, the material temperature is calculated as 729°C (1345°F). Table I shows that the calculated fast fracture probability of survival exceeds 99.99% for all 60 vanes for this highest stress condition, as well as for all the other emergency shutdown combustor pattern conditions.

Table I.
Turbine emergency shutdown.

	Bounding combustor pattern		
	Maximum inner gradient	Maximum temperature	Maximum outer gradient
Max stress MPa (ksi)	208 (30.2)	175 (25.4)	199 (28.9)
Vane set probability of survival	>0.9999	>0.9999	>0.9999
Temperature at max stress location °C (°F)	729 (1345)	743 (1370)	732 (1350)
Location	Midspan trailing edge	Midspan trailing edge	Midspan trailing edge

Table II.
Turbine maximum continuous power.

	Bounding combustor pattern		
	Maximum inner gradient	Maximum temperature	Maximum outer gradient
Max stress MPa (ksi)	169 (24.5)	121 (17.6)	150 (21.8)
Vane set probability of survival	>0.9999	>0.9999	>0.9999
Temperature at max stress location °C (°F)	1182 (2160)	1277 (2330)	1238 (2260)
Location	Midspan trailing edge	Midspan trailing edge	Midspan trailing edge

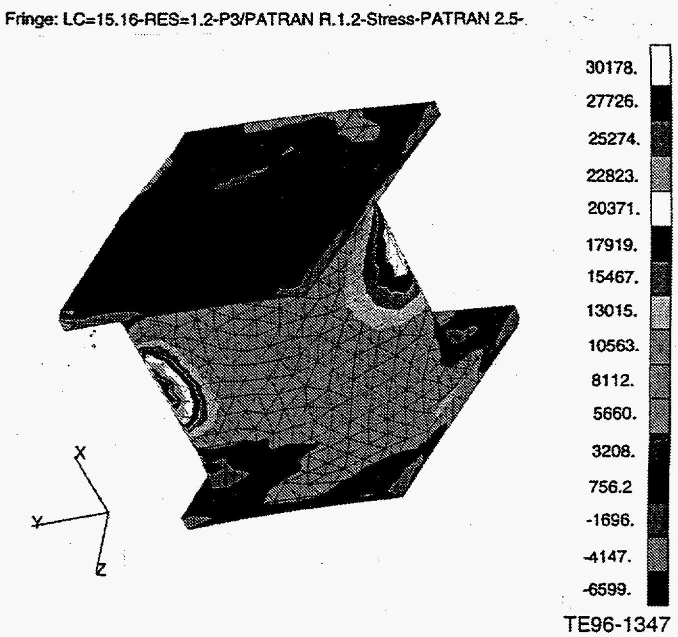

Figure 5. Ceramic vane, 0.9 sec after emergency shutdown - MIG condition.

Figure 6 shows that the highest calculated stress is 169 MPa (24.5 ksi) at conditions of maximum continuous power and the maximum inner gradient bounding combustor temperature pattern. Table II indicates that this is the highest steady-state stress calculated in the ceramic vane and that the fast fracture probabilities of survival exceed 99.99% for all steady-state conditions evaluated. The ceramic material temperature is about 1182°C (2160°F) at the trailing edge location of maximum stress.

LONG-TERM LIFE

Verification of long-term materials life at the maximum steady-state stress and temperatures of the ceramic vane is needed prior to a long-term demonstration at a commercial site. Although the life of the ceramic with the best long-term stress rupture performance of materials tested to date should be adequate for a 4000 hr turbine demonstration (Norton, P., et al., 1995), that ceramic was judged questionable in this program for a typical 30,000 hr industrial turbine design life, especially considering uncertainties in the combustor temperature pattern.

Some newer silicon nitrides (e.g., AS800, SN281) offer promise for improved lifetimes. However, there is insufficient long-term material data for these materials at durations from 5,000 to 10,000 hr to verify their use in a commercial turbine demonstration. The decision on which material to use in the engine

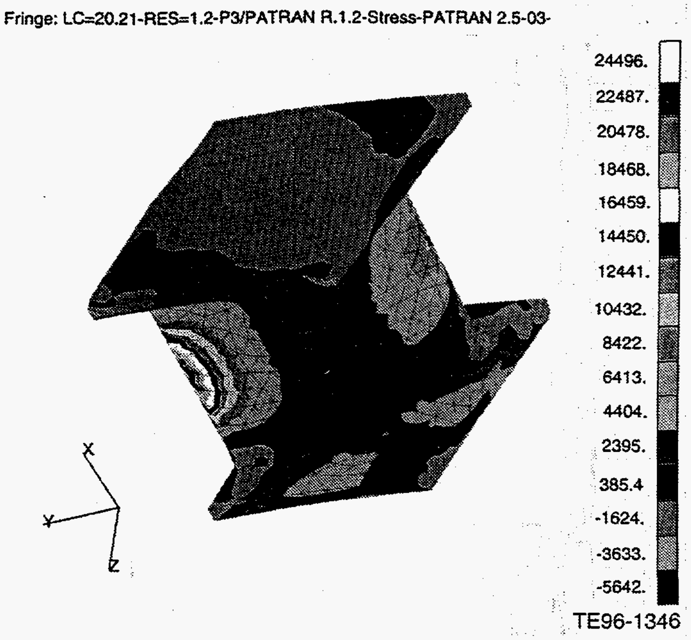

Figure 6. Ceramic vane, steady-state - MIG condition.

will consider results of additional long-term ceramics tests that are being conducted at Oak Ridge National Laboratories (ORNL) and the University of Dayton. From 5,000 to 10,000 hr of long-term testing of materials should be completed by the time the ceramic vanes will be installed in the engine.

RELEVANCE OF MODEL 501 TURBINE DEMONSTRATION TO ATS

An earlier paper (Wenglarz, et al., 1996) discussed improvements in power and efficiency for ATS turbines associated with use of ceramics to alleviate chargeable cooling requirements for vanes and blades. Considering both economics and risk, that paper concluded that a promising location to introduce ceramic airfoils would be the highest temperature row where cooling of metallics would be required, but cooling of ceramics would not. For the high inlet temperature ATS turbines, that location corresponds to the second-stage vanes. This conclusion is based on the review of the available long-term stress rupture data for structural ceramics mentioned earlier. Anticipating some life improvements will be shown in tests of newer ceramics, the temperature limit for uncooled ceramics was judged to be less than 1315°C (2400°F) at stresses in the 172 to 206 MPa (25 to 30 ksi) range to achieve typical industrial turbine vane and blade design lifetimes in the 30,000 hr range. This stress rupture limit does not consider the effects of dynamic oxidation of the ceramic in the high velocity combustion stream, which are apparently unknown at this time.

The Model 501 turbine ceramic first-stage vane retrofit and demonstration described in this paper should provide a stepping stone to implementation of ceramic second-stage ATS turbine vanes because of comparable flow path conditions. The external combustor for the Allison ATS turbine is predicted to produce a flatter temperature pattern than the Model 501 turbine combustors. This results in lower expected peak temperatures and temperature gradients entering the second stage of the Allison ATS turbine than for the first-stage ceramic vanes of the Model 501 turbine which will be demonstrated at a commercial site.

SUMMARY AND CONCLUSIONS

The thermal and stress analyses of the Model 501 ceramic vane first-stage design have calculated acceptable fast fracture stress levels and probabilities of survival exceeding 99.99% for turbine continuous power and emergency shutdown (thermal shock) conditions. The calculated maximum steady-state vane stress is 169 MPa (24.5 ksi) at a material temperature of 1182°C (2160°F).

Although analyses in this and another program (Norton, et al., 1995) suggest that several Si_3N_4 ceramics have acceptable fast fracture properties, additional long-term testing of the most promising of these ceramics is needed to verify lifetimes up to 30,00 hr, which is a typical design goal for industrial turbine vanes and blades. Results of long-term materials tests in progress at ORNL and the University of Dayton will be used to choose the ceramic material for the long-term turbine demonstration.

The ceramic materials temperatures, thermal gradients, and thermal shock conditions of uncooled second-stage ceramic vanes of an ATS turbine are expected to be somewhat less severe than those environments for the first-stage ceramic vanes of the Model 501 turbine, which will be demonstrated at a commercial site.

ACKNOWLEDGMENTS

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