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THERMOMECHANICAL EFFECTS IN HIGH-SPEED SEAL RUBS

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Final Report

NASA Research Grant NSG 3253

Covering Period from February 26, 1979 to December 31, 1984

Submitted to

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

by

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Dartmouth College
Hanover, New Hampshire 03755

June 1987

THAYER
SCHOOL OF
ENGINEERING
DARTMOUTH COLLEGE

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INTRODUCTION

Much effort has been devoted in recent years to the development of more efficient and economical gas turbines for both transportation and power generation. These developments require improved designs of engine components. Among the most important components, from a standpoint of engine efficiency, are the gas path seals which prevent the flow of working fluid (primarily air) around rotating engine components. A typical large turbine engine may contain 50 or more gas path sealing locations, with most of these seals being one of two types, blade tip seals or labyrinth seals. In either type of seal, the rate of gas leakage is very dependent on the clearance maintained between rotating and stationary seal component. The cumulative seal leakage can significantly decrease the power output and efficiency of the engine, with the efficiency penalty approaching 10 percent at large values of seal clearance. It is important, therefore, to reduce clearances between stationary and rotating components of gas path seals in order to decrease an engine's specific fuel consumption and increase its efficiency.

Although reductions in seal clearance have a very desirable effect on efficiency, they result in occasional rubbing contact between rotating and stationary seal components during engine operation. These rubs, which are caused by differential thermal expansion of engine components and by transient engine deflections, occur at very high sliding speeds, sometimes exceeding 400 m/s. They can result in high sliding surface temperatures, excessive wear of the seal components, and possible damage to the engine. To maintain a small steady-state seal clearance and to avoid damage to the rotor, it is desirable that the stationary seal component (the gas path seal material) wear instead of the rotating component during rub situations.

A variety of "abradable" materials has been developed for use in gas path seals, but none of the materials has been completely successful. These materials, which have often been developed by a trial-and-error process, have too frequently caused excessive wear of the rotating component, (either blade tips or labyrinth seal knife edges) and excessive surface temperatures, resulting from frictional heating. One of the main factors retarding the development of better abradable seals is our incomplete understanding of the thermal and mechanical phenomena which occur during gas path seal rubs. The improvement of our understanding of these "rub energetics" phenomena, and of the material and design parameters which affect them, has been the primary objective of this research. The research was carried out at the Thayer School of Engineering, Dartmouth College during the period February 1979 to December 1984.

SUMMARY OF RESULTS

This research program at the Thayer School of Engineering was supported by NASA Grant NSG3253, entitled Thermomechanical Effects in High Speed Seal Rubs. The research had two thrusts, experimental and analytical, and good progress was made in both areas.

The analytical effort was aimed at development of numerical models of the thermal and mechanical phenomena which occur during seal rubs. The models follow the guidelines described in a published paper [1].* Finite element programs have been developed for studying the temperatures that result from frictional heating during rubs [2,7,22], and the plastic deformation which is caused by rub forces [6,9,10,17,23]. The temperature analysis program has been used to predict, with good accuracy, surface and sub-surface temperature distributions in both labyrinth and blade tip seal configurations [2,4,7]. It has been used to determine the influence of various geometric and material parameters on rub surface temperatures [2,4,8]. More recently two plasticity analysis programs have been developed for studying the severe deformations which occur in both blade tip and stationary seal component during a blade tip seal rub. The first is a viscoplastic model which gives good predictions of the residual plastic deformations in a single pass of blade tip over a fully dense seal segment [6]. The second program enables the study of plastic deformations in porous metallic seal materials, and its predictions have been experimentally verified for single passes of a hard blade tip over porous fibermetal seal segments [10,23]. This analysis has given rise to some ideas for seal configurations which would wear (or abrade) more easily when deformations of this type are encountered [9,10].

The experimental phase of this project was originally intended to aid in verification of the results of the analytical model. The tests have not only enabled this verification, but have also led to some very interesting and significant experimental findings. Two devices have been built and tested, one for studying labyrinth seal configurations and one for blade tip configurations [16]. The labyrinth, or knife edge, device has been used primarily for studying surface temperatures during continuous rubbing [2]. Of more significance, perhaps, is the blade tip test device, which is a novel pendulum-type, single pass rub tester. This device has enabled the study of deformations and temperatures during a single rub of blade tip against a seal segment [3,4,5]. Although the rub velocity is lower than that in a typical turbine engine blade tip seal, it enables fundamental information about rub phenomena to be gained from simple, inexpensive tests of actual seal materials [4]. The device has been used to measure the abradability of both commercially available seal materials [3,5] and potential seal designs and materials [9,10,17,21], and to study the influence of blade tip geometry on rub phenomena [5,18]. Experimental techniques have also been developed for measuring surface temperatures and deformations during single pass rubs [4,17]. Modifications have been made to the device to permit testing at both high temperatures (up to 500°C) [20] and cryogenic temperatures (down to -190°C) [19].

The single pass tester appears to have substantial potential as a device for studying rub energetics phenomena, although that potential has only begun to be tapped. Seal material and turbine manufacturers have shown considerable interest in the tester and at least one such manufacturer has already built a copy of the device in their laboratory.

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*Numbers in brackets refer to publications and presentations listed in a later section of this report.

CONCLUSIONS FROM THE RESEARCH

Among the most significant findings of the research so far are the following:

1. The energy lost by the moving abrader in a pendulum-type test device, at a given incursion depth, is a good measure of a material's abradability, although specific energy (energy loss/unit wear) might be a better measure of the abrasion resistance of less abradable (more abrasion resistant) materials.

2. Specific energy loss during rubs of porous abradable materials is a function of the actual rake angle of the abrader. This angle is determined by the nominal rake angle, radius of leading edge (which may be modified by wear and transfer) and depth of incursion. A more negative rake angle leads to densification, less material removal, and slightly more energy loss. Energy loss is affected much less than specific energy loss by the abrader rake angle.

3. For a given abradable material, abradability generally decreases (or rub energy increases) as the density increases and as the tensile strength increases.

4. Densification of a porous surface during a rub causes an increase in rub energy dissipation in subsequent rubs.

5. An increase in test temperature resulted in an increase in energy (or a decrease in abradability) for porous copper fibermetal. Specific energy loss decreased, however.

6. An increase in test temperature resulted in a decrease in both energy loss and specific energy loss for solid copper specimens.

7. Softened, annealed copper showed higher specific energy losses than the same material in a work-hardened condition. This may be because these materials wore by a chip formation mechanism in these tests, and the chip formation was accompanied by more plastic deformation in the case of the softer material.

8. A specimen composed of a thin solid copper layer on a copper fibermetal base showed abradability midway between that of fibermetal and that of solid copper.

9. A region of severe deformation develops near the sliding surface during the first pass of a slider over a metallic (copper) specimen.

10. The depth of the severely deformed zone increases in subsequent passes over the same surface.

11. A finite element viscoplasticity analysis program has been written which proved capable of modelling the severe plastic deformations in the contact zone of fully-dense metals. Agreement between analysis and experiment was obtained if it was assumed that the slider adheres to the specimen surface about 10% of the time it is in contact.

12. Both analysis and experiment showed that a narrower contact zone results in less subsurface deformation in fully-dense seal materials.

13. Nearly all (more than 90%) of the frictional energy in fully-dense metals is dissipated either on the contact surface or within 5 microns of that surface.

14. The abradability of a seal material is governed by the most efficient wear mechanism. In labyrinth seals, in which continuous sliding occurs in the contact zone, plastic deformation is the rate-controlling mechanism, whereas in blade tip seals, in which the seal segment sees intermittent contact, chip formation is a more efficient wear mechanism.

15. The near-surface plastic deformation and abradability of a fully-dense seal material can be substantially increased by the addition of thin lamellae of a soft ductile material, oriented perpendicular to the sliding direction. The gain in abradability is greatest in continuous sliding cases.

16. Finite element viscoplastic analysis of porous materials, taking the compressibility of the porous metal into account, can give good predictions of the plastic deformation in porous abradable seal segments.

17. The plastic deformation near a sliding contact in a porous material is different from that in a fully-dense metal. In a porous metal there is a tendency for compressive deformation ahead of the slider, whereas there is a slight bulge in that region with dense solids.

18. A sharp trailing edge of the slider increases material removal rates when rubbing against porous metals. Material behind the slider lifts up from the surface, especially with sharp trailing edges, and this prepares the surface for enhanced wear in subsequent passes.

19. Subsurface heat generation would not be expected to cause a subsurface temperature peak in the stationary rub specimen, but such a subsurface peak could occur in the blade tip.

20. A study of the influence on surface temperatures of various material properties showed that increased thermal conductivity of the stationary component played a significant role in lowering contact temperatures. Increased thermal conductivity of the moving blade tip component and increased thermal diffusivity of the stationary material can also have a beneficial effect. Lower yield stress and, to a lesser extent, lower modulus of elasticity and lower coefficient of thermal expansion can also result in decreased surface temperatures by increasing contact zone sizes and decreasing heat generation rates.

PUBLICATIONS AND PRESENTATIONS RESULTING FROM RESEARCH

Technical Papers (copies attached)

1. F.E. Kennedy, "Thermomechanical Phenomena in High Speed Rubbing", Wear, vol. 59, 1980, pp. 149-163
2. F.E. Kennedy, "Surface Temperatures in Sliding Systems - A Finite Element Analysis" ASME J. Lubrication Technology, v. 103 (1981) pp. 90-96.
3. F.E. Kennedy and N.P. Hine, "Single-Pass Rub Testing of Abradable Seal Materials" Lubrication Engineering, v. 38 (1982), pp. 557-563
4. F.E. Kennedy, "Single-Pass Rub Phenomena - Analysis and Experiment" ASME J. Lubrication Technology, vol. 104 (1982), pp. 582-588
5. F.E. Kennedy, "Factors Affecting Abradability of Porous and Fully-Dense Metals" Wear of Materials, 1983, ASME (1983), pp. 153-160
6. F.E. Kennedy and L.P. Grotelueschen, "Determination of Near-Surface Plastic Deformation in Sliding Contacts", J. Applied Mechanics, vol. 51 (1984), pp. 687-689
7. F.E. Kennedy, F. Colin, A. Floquet and R. Glovsky, "Improved Techniques for Finite Element Analysis of Sliding Surface Temperatures", Developments in Numerical and Experimental Methods Applied to Tribology, Butterworths, London (1984), pp. 138-150
8. F.E. Kennedy, "Thermal and Thermomechanical Effects in Dry Sliding" Wear, v. 100 (1984), pp. 453-476
9. F.E. Kennedy, L.A. Hartman, K.E. Hauck and V.A. Surprenant, "The Role of Plastic Deformation in the Wear of Lamellar Solids", Wear of Materials 1985, ASME (1985), pp. 273-279
10. F.E. Kennedy, K.E. Hauck and L.P. Grotelueschen, "Plastic Analysis of Wear Phenomena as an Aid in the Development of Abradable Materials", in Mechanisms and Surface Distress, Dowson, et al., eds., Butterworths, London (1986), pp. 67-73

Other Presentations

11. F.E. Kennedy, "A Thermomechanical Model of Gas Path Seal Rubs" presented at NASA/Air Force/Army Gas Path Seal Rub Energetics Workshop, Cleveland, December , 1980
12. F.E. Kennedy, "Thermal and Mechanical Rub Phenomena" presented at Air Force/NASA Rub Energetics Workshop, Wright -Patterson AFB, Ohio March, 1982
13. L.P. Grotelueschen and F.E. Kennedy, "Surface and Near-Surface Deformation in Sliding Contacts",presented at 9th U.S. National Congress of Applied Mechanics, Ithaca, NY, June 1982

14. F.E. Kennedy, "Thermomechanical Effects in High Speed Rubs" presented at NASA/Air Force/Army Gas Path Seal Rub Energetics Workshop, Cleveland, Ohio, December 1983
15. F.E. Kennedy, K.E. Hauck and L.P. Grotelueschen, "Plasticity Analysis of Wear Phenomena", presented 22nd Annual Meeting of Society of Engineering Science, University Park, PA., October 1985

Student Theses and Reports

16. N.P.Hine, "Two Devices for the Study of the Energetics of High Speed Seal Rubs" Master of Engineering Thesis, Thayer School of Engineering, Dartmouth College, June 1982
17. L.P. Grotelueschen, "Investigation of Single Pass Rub Phenomena Towards Improved Gas Path Seal Materials", Master of Engineering Thesis, Thayer School of Engineering, Dartmouth College, June 1982
18. R.R. Endo, "Modifications of the Single Pass Rub Test Device", Bachelor of Engineering Project Report, Thayer School of Engineering, Dartmouth College, June 1981
19. Y.D. Chew, "Single Pass Rub Testing Device for Cryogenic Temperatures" Bachelor of Engineering Project Report, Thayer School of Engineering, June 1982
20. P. Berglund, "Development of a High Temperature Abrasion Tester" Bachelor of Engineering Project Report, Thayer School of Engineering, June 1982
21. S.A. Cooper, "A Study of Fibermetal with a Brazed Sheet as a Gas Path Seal Material" Seniors Honors Thesis, Dartmouth College, June 1982
22. R.P. Glovsky, "Development and Application of THERMAP" Master of Engineering Thesis, Thayer School of Engineering, June 1982
23. K.E. Hauck, Jr., "A Finite Element Study of Blade Tip Rub Interactions in Gas Path Seals", Master of Engineering Thesis, Thayer School of Engineering, January, 1985

Note: Copies of all papers, theses, and reports listed above have been sent previously to the technical monitors at NASA Lewis Research Center

APPENDIX

COPIES OF TECHNICAL PAPERS RESULTING FROM RESEARCH

1. F.E. Kennedy, "Thermomechanical Phenomena in High Speed Rubbing", Wear, vol. 59, 1980, pp. 149-163
2. F.E. Kennedy, "Surface Temperatures in Sliding Systems - A Finite Element Analysis" ASME J. Lubrication Technology, v. 103 (1981) pp. 90-96.
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