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THERMOSTRUCTURAL RESPONSES OF CARBON PHENOLICS IN A RESTRAINED THERMAL GROWTH TEST

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I. INTRODUCTION

The thermostructural response of carbon phenolic components in a solid rocket motor (SRM) is a complex process. It involves simultaneous heat and mass transfer along with chemical reactions in a multiphase system with time-dependent material properties and boundary conditions.

In contract to metals, the fracture of fiber-reinforced composites is characterized by the initiation and progression of multiple failures of different modes such as matrix cracks, interfacial debonding, fiber breaks, and delamination. The investigation of thermostructural responses of SRM carbon phenolics is further complicated by different failure modes under static and dynamic load applications.

Historically, there have been several types of post-firing anomalies found in the carbon phenolic composites of the Space Shuttle SRM nozzle. Three major failure modes which have been observed on SRM nozzles are pocketing (spallation), ply-lift, and wedge-out. In order to efficiently control these anomalous phenomena, an investigation of fracture mechanisms under NASA/MSFC RSRM (Redesigned Solid Rocket Motor) and SPIP (Solid Propulsion Integrity Program) programs have been conducted following each anomaly.

This report reviews the current progress in understanding the effects of the thermostructural behavior of carbon phenolics on the failure mechanisms of the SRM nozzle. A literature search was conducted and a technical bibliography was developed to support consolidation and assimilation of learning from the RSRM and SPIP investigation efforts. Another important objective of this report is to present a knowledge-based design basis for carbon phenolics that combines the analyses of thermochemical decomposition, pore pressure stresses, and thermostructural properties. Possible areas of application of the knowledge-based design basis include critical material properties development, nozzle component design, and SRM materials control.

II. LITERATURE SEARCH ON CARBON PHENOLICS FOR SRM NOZZLE

A. Carbon Phenolics

There are four groups of test data available for different SRM carbon phenolic materials:

1) Avtex preshutdown rayon, before 1988 initial shutdown,
2) Avtex postshutdown rayon, after 1988 initial shutdown,
3) NARC (North American Rayon Corporation), rayon selected to develop an Avtex clone, and
4) PAN (polyacrylonitrile), an alternative to rayon.

B. Anomalies on SRM nozzle

Pocketing is referred to the tensile failure of fill fiber yarn in the resin pyrolysis zone. It is caused by the across-ply expansion of pyrolysis gases in a restrained environment. Another failure phenomenon, "ply-lift", is considered to be caused by the across-ply tensile or interlaminar shear stresses, driven by across-ply thermal expansion, during resin volatilization or pyrolysis. "Wedge-out" is hypothesized as an interlaminar failure of the outer charred material as a result of the small interlaminar surface area at the corners of adjacent rings.

C. Technical Reports

Five groups of test report on thermal and mechanical properties of SRM carbon phenolics, as well as two failure mechanism related test programs are listed below.

1. AVTEX PRESHUTDOWN/NTA: 1986 - 1989.
2. AVTEX PRESHUTDOWN/SPIP/NIP: 1988 - 1991.
3. AVTEX POSTSHUTDOWN: August 1990.
4. NARC: 1990 - present.
5. PAN: 1989 - present.
6. Permeability: 1988 - present.
7. Ply-lift: 1988 - present.

In addition, research papers in the study of thermochemical expansion of polymer composites during matrix decomposition were also searched and reviewed. Science and engineering fundamentals of thermochemical response of polymer composites, simultaneously decomposing and thermal expanding during the rapid heating, were discussed in these papers.

III. THERMOSTRUCTURAL ANALYSIS PROPERTIES OF COMPOSITES

A. Critical Material Properties

The thermostructural response of carbon phenolics exposed to the severe SRM exhaust environment have been observed to occur in three distinct temperature regions. Thus, the critical material property parameters needed for thermostructural analysis of SRM carbon phenolics have to be related to the phase changes occurring in these temperature regions. The evaluation and qualification efforts of carbon phenolics have been aimed at correlating these thermostructural properties with the failure modes observed in flight and static rocket motors.

Pocketing is induced by excess fiber tensile strains and subsequent fracture of fiber. Therefore, fill tensile strength is a critical property. Ply-lift is referred to the inter-ply failure and subsequent lifting between plies. Wedge-out is associated with ply angle and adjacent ring interactions across bondlines.

Therefore, across-ply coefficient of thermal expansion, across-ply tensile strength, and interlaminar shear strength are identified as the critical material properties for these two anomalies.

B. Restrained Thermal Growth (RTG) Tests

To include the pore-pressure stress, which is generated by pyrolysis gases, into the analysis of stress-strain curves, a combined effect of temperature increase on internal gas pressure and thermal expansion of composites has to be considered in investigating the thermostructural response. The Restrained Thermal Growth test represents this type of test where stiffness, thermal expansion, thermal decomposition, and strength characteristics interact as functions of temperature and heating rate. By simulating the flight environment of a SRM nozzle, the effect of internal gases on the thermostructural response as well as the resistance to pocketing failure can be measured.

In the restrained-strain environment, the internal gases will escape through the pores and microcracks of the material. Since the stress fields affect the extent of microcracking, stress fields also affect the permeability of gases, which in turn affects the stress fields via the variation of pore pressure.

By correlating the lateral strain measured from a RTG test to the fill tensile stress-strain curves, after subtracting out the free thermal expansion, the fill tensile stress on fill fiber can be calculated. Assuming that the fiber yarn is a homogeneous material, the maximum transverse shear stress on the fiber can be estimated by an in-plane tensile stress (pulling the yarns) due to lateral strain and an across-ply compressive stress (crushing the yarns) due to compressive load. Therefore, from the lateral strain and compressive stress, the in-plane fiber failure stress and the temperature at which pocketing occurs can be determined.

Other important material properties revealed from RTG tests are the first peak temperature (T_g), stress at T_g, saddle stress, second peak stress (the ultimate stress), and failure/explosive blowout temperature.

Comparison between the RTG responses of several Avtex-Preshutdown specimens at 1°F/sec and 10°F/sec heating rates indicated that at the higher heating rate, the gases had less time to migrate to the free surface and the internal pressure increased faster. Consequently, the stresses at both peaks are much higher than those at lower heating rate. RTG responses of two PAN-based specimens, Amoco 23 and FM5834, are shown in Figures 1 and 2, respectively. In-plane permeability of Amoco 23 has been shown to be extremely low, lower than any other measured PAN-based material. The single high peak stress (>30 kpsi) of this RTG response revealed the effect of low permeability on RTG response. Visual inspection of the tested specimen indicated that the specimen failed by explosive blowout with both fill and warp yarn failures. On the contrary, the FM5834 RTG response shows a well-defined two peaks and low peak stresses. Another important feature of this PAN-based RTG response is that following the second peak, the stress declines gradually, indicating that, with a completely developed pathway for internal pyrolysis gases, the gases readily bled off to the free surface and the compressive stress decreased to zero without an explosive blowout.

From RTG data, it is clear that carbon phenolic permeability and pyrolysis/volatilization gases are two important variables affecting the failure mechanism. Therefore, material permeability is considered as a critical variable which can be used to control the pocketing anomaly.

V. SUMMARY AND RECOMMENDATIONS

Thermostructural responses and failure mechanisms of a series of carbon phenolics, including rayon- and PAN-based, have been investigated. The result indicated that there is a close relationship between these two materials behaviors. Three critical property parameters in the thermostructural responses of carbon phenolics in a RTG test have been reviewed. Possible explanation of the difference in RTG responses, based on the effect of gas permeability on the internal gas pressure, has been explored. It is recommended that more testing of these three critical properties, having a capability to elucidate their combined effects on controlling the failure mechanism, be conducted at different temperatures. It was founded from the test results of PAN based specimens that resin to fiber bonding plays an important role in determining the thermostructural properties of the composites. An investigation into its effect on gas permeability and failure mechanisms is recommended.

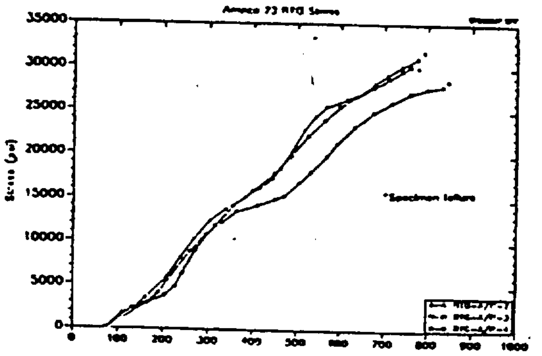

Figure 1 Amoco 23 Phase III RTG A/P Compressive Stress vs. Temperature Response

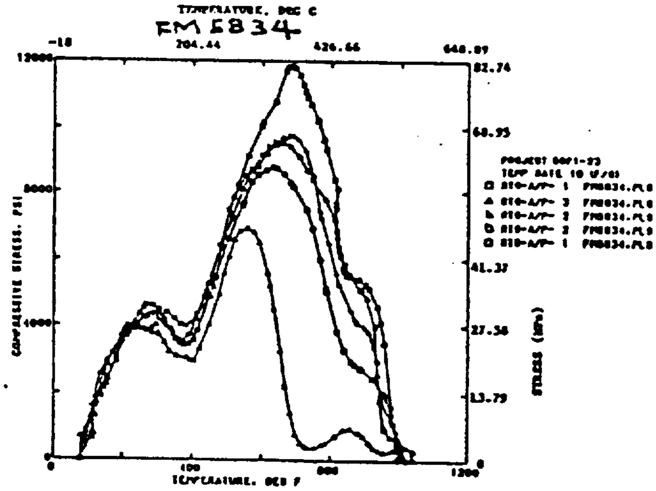

Figure 2 Stress as a Function of Temperature (RTG Constant Strain Mode)