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NDE for Material Characterization in Aeronautic and Space Applications

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Abstract

This paper describes selected nondestructive evaluation (NDE) approaches that were developed or tailored at the NASA Glenn Research Center for characterizing advanced material systems. The emphasis is on high-temperature aerospace propulsion applications. The material systems include monolithic ceramics, superalloys, and high temperature composites. In the aeronautic area, the highlights are cooled ceramic plate structures for turbine applications, γ-TiAl blade materials for low-pressure turbines, thermoelastic stress analysis (TSA) for residual stress measurements in titanium based and nickel based engine materials, and acousto ultrasonics (AU) for creep damage assessment in nickel-based alloys. In the space area, examples consist of cooled carbon-carbon composites for gas generator combustors and flywheel rotors composed of carbon fiber reinforced polymer matrix composites for energy storage on the international space station (ISS). The role of NDE in solving manufacturing problems, the effect of defects on structural behavior, and the use of NDE-based finite element modeling are discussed. NDE technology needs for improved micro-electronic and mechanical systems as well as health monitoring of micro-materials and components are briefly discussed.

1 Aeronautic Applications

In the first two applications discussed below, the focus is on ceramic material optimization and superalloys' resistance to defects, respectively. In the last two applications discussed below, the emphasis is on NDE methods that can gauge residual stress, and characterize creep damage/remaining life in superalloys, respectively.

1.1 Cooled ceramic vane materials

Tough high temperature materials that are light in weight and can operate with minimal cooling are needed to improve the efficiency of gas turbine engines by increasing the operating temperature and/or decreasing the cooling air [1]. In-situ toughened silicon nitride ceramics are potential candidates because of their low density and high temperature strength. High processing cost was found to be the "bottle neck" in the manufacturing of these ceramics. Advanced rapid prototyping and layered manufacturing are being used for minimally-cooled and functionally-graded ceramic structures at NASA Glenn Research Center because these techniques can provide low cost processing of engine parts [2]. NDE is used for process optimization and defect analysis. In addition, 2D and 3D finite element analysis are used to optimize the cooling channel geometry and spacing to reduce thermal stresses as well as to help evaluate thermal and environmental barrier coatings.

1.2 γ-TiAl blade materials

γ-TiAl is a good low-density, high-strength material for low-pressure turbine blade applications in aircraft engines. However, because of its low ductility (relatively brittle behavior), its lack of resistance to defects and/or damage can substantially degrade its fatigue properties. In this study, specimens, rejected due to NDE indications, were fatigue-tested to identify critical defects that may affect fatigue life. Microfocus x-ray radiography was utilized to correctly detect/identify the critical defects (Fig. 1). However, the size of defects was almost always overestimated due to the complex nature of the micro-shrinkage porosity [3]. In addition, radiography often imaged a "halo" around the defect that was possibly due to some chemical inhomogeneities. It was unclear from NDE alone which parts of the indication are important to the fatigue cracking process. This led to overestimating the contribution of the casting defect on fatigue crack initiation. However, the end result showed that fatigue strengths can be reasonably predicted based on loading conditions and defect size [3].

1.3 Residual stress measurements via thermoelastic stress analysis

TSA is an NDE technique based on the fact that materials experience small temperature changes when compressed or expanded. When a structure is cyclically loaded (i.e., cyclically compressed and expanded), a surface temperature profile results which correlates to the stress state of the structure's surface. The surface temperature variations resulting from a cyclic load are measured with an infrared camera. Traditionally, the temperature amplitude of a TSA signal was theoretically defined to be linearly dependent on the cyclic stress amplitude (i.e., the changing stress). As a result, the temperature amplitude resulting from an applied cyclic stress was assumed to be independent of the cyclic mean stress. In [4], it was shown that mean stresses significantly influenced the TSA results for titanium-based alloys (Fig. 2) and nickel-based alloys. For example, in the case of Ti-6Al-4V, a 276 MPa (40 ksi) change in mean stress caused an 8% change in the TSA results as represented by the IR signal values in Fig. 2. The smallest statistically significant change in mean stresses was observed to be 69 MPa (10 ksi). Further refinement of the TSA technique was accomplished by developing accurate temperature correction curves. These curves are required since the thermoelastic temperature change is also highly dependent on the specimen's absolute temperature. In addition, the non-linear TSA response was studied by allowing the TSA system to capture the second harmonic response by developing a linear frequency doubler and placing it in-line with the load cell reference signal. It should be noted that the first harmonic of the thermal response is a function of the cyclic stress amplitude and the mean stress while the second harmonic is a function of the square of the stress amplitude. By capturing both harmonics, the stress amplitude and the mean stress at a given point on a structure subjected to a cyclic load can be simultaneously obtained. Lastly, comparisons between the experimental data and theoretical predictions showed good agreement. As a result, confidence was achieved concerning the ability to simultaneously obtain values for the static stress as well as the cyclic stress amplitude of structures. The observable differences in the mean stresses, from 69 to 207 MPa (10 ksi for titanium based to 30 ksi for nickel based materials), are sensitive enough for useful monitoring of residual stresses on the order of yield stresses of 930 MPa (135 ksi). Because the mean stress sensitivity was established in [5] for both nickel and titanium alloys, it is now feasible to establish a protocol that would enable the monitoring of residual stresses in structures utilizing the TSA technique.

1.4 Creep damage assessment via acousto-ultrasonics

The objectives are to develop quantitative measures of damage or remaining life in hot section parts by assessing the feasibility of NDE methods and by studying degradation assessment of material/mechanical properties via NDE data [6]. AU measurements, as represented by the centroid of the power spectrum, are shown in Fig. 3 as a function of position along a stepped creep specimen. The areas of each step were chosen to produce various levels of damage. The stresses in each step corresponded to fractional lives representing 12.5%, 25%, 50% and 100%. The 100% life relates to creep fracture in the smallest area (i.e., highest stressed step). The specimen design allows for convenient post-mortem NDE analysis of creep damage in a failed specimen. The AU measurements proved sensitive to damage at 50% and 100% of used up life separate from thermal exposure. Further, AU maximum centroid of power values increased with time-to-failure and segregated between the 1350 °F and the 1500 °F populations (Fig. 4). Further findings from [6] are 1) stepped creep specimens are useful for NDE in quantifying remaining creep life, and 2) Eddy current substantiated AU findings in gauging the creep damage separate from thermal exposure.

2 Space Applications

The focus in both applications is on assuring material/component quality and uniformity via NDE and on demonstrating the importance of integrating NDE and FEM for rapid and reduced cost in proof testing and material development of advanced composites.

2.1 Cooled carbon-carbon composite for gas generator combustors

The objective is to assure quality and uniformity in manufacturing and to further the understanding of damage due to thermal and mechanical testing. The latter will be achieved by correlating before- and after-testing NDE with the material thermomechanical properties based on FEM, and with metallographic sectioning where applicable. Figure 5 shows the radiographic and tomographic capabilities in detecting problems, errosion in metallic cooling tubes and nonuniform brazing, due to the application of brazing cycles. These findings guide the NDE-based FEM modeling of space component [7], a key to rapid and reduced cost in proof testing and material development.

2.2 Polymer matrix composite for flywheel based energy storage system

Composite flywheels are being developed in lieu or to complement expensive and short-life chemical batteries. Furthermore, they promise order of magnitude increases in performance and service life for several NASA aerospace energy storage applications. Rotor certification for safe life, where NDE plays a major role, is the challenge to overcome before these advanced flywheels reach operational status. NDE combined with stress analysis and life prediction are expected to set a standardized procedure to accurately assess the applicability of using various composite materials to design a suitable rotor/flywheel assembly. Carbon fiber reinforced polymer composites are being considered for energy applications because of the high energy and power densities they possess [8] and that composite design allows burst failure modes that are relatively benign in comparison to flywheels made of metallic materials [9].

Structural assessment of a flywheel rotor assembly by integrating FEM and NDE of a cylindrically-shaped composite rotor with hollowed hub design is presented. Detailed analyses under combined centrifugal and interference fit loading was performed. Three-dimensional analyses and two-dimensional fracture mechanics analyses were conducted and comparison of the results obtained with those extracted via NDE findings are reported. Cracks due to rotational loading up to 34000 rpm were successfully imaged with NDE (Fig. 6) and predicted with 3D FEM (Fig. 7). A procedure that extends current structural analysis to life prediction tool was also defined [10]. Pancake type composite rotors with a solid hub design were also evaluated by using acousto ultrasonic decay rate to classify the rotors before testing and to study damage assessment after testing (Fig. 8). Only flywheels from (d) and (e) were properly classified by AU and reached desired 40,000 to 45,000 rpm before first matrix cracking, those from (a), (b), and (c) depicted large scatter in the signal. AU from after testing data was found to be a viable NDE technique for gauging life degradation of composite rotors.

2 MEMS and Health Monitoring

Glennan Microsystem Initiative, a joint industry-government-university program led by NASA Glenn research center since 1998, is poised to develop physical and chemical microsensors and microactuators for operation in harsh environments (high temperature power and radiation, humidity, etc…). The technologies include harsh environment electronics, micro-power, wireless communications, signal processing, material development, and micro fabrication methods development (www.glennan.org). Many relevant papers in the areas of smart sensors, MEMS and health monitoring can be found in [11].

3. Conclusions

The critical role of nondestructive evaluation as a material characterization modality was demonstrated for several aerospace applications. NDE was successfully used for ceramic process optimization and γ-TiAl effect of defect investigation on fatigue life. Thermoelastic stress analysis was found to be a viable NDE method to monitor the residual stress-state of structural materials. Acousto ultrasonics parameters were capable of quantifying creep damage starting at 50% of used up life and correlated well with time-to-failure and used up life in superalloys. Microfocus radiography and computed tomography in conjunction with finite element modeling and fracture analysis proved to be useful for rapid and reduced cost in proof testing and material development of advanced composites. Lastly, acousto ultrasonics was able to classify flywheel material systems and gauge degradation due to spin testing of composite rotors.

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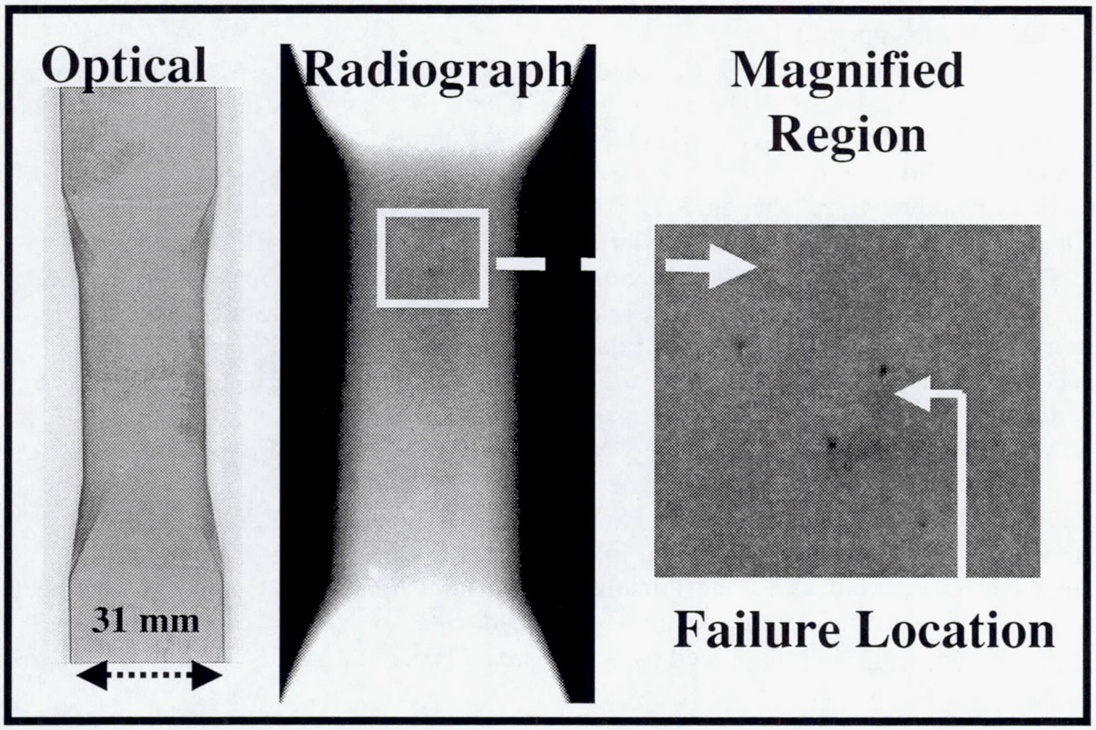


Fig.1- Γ-TiAl sample where failure location is not at largest micro-shrink porosity

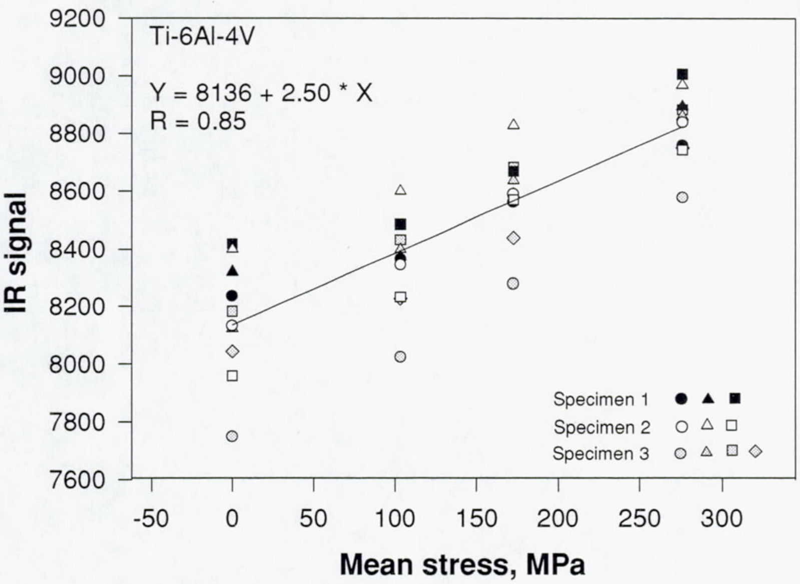


Fig.2- The mean stress dependence IR signal range for Ti-6Al-4V

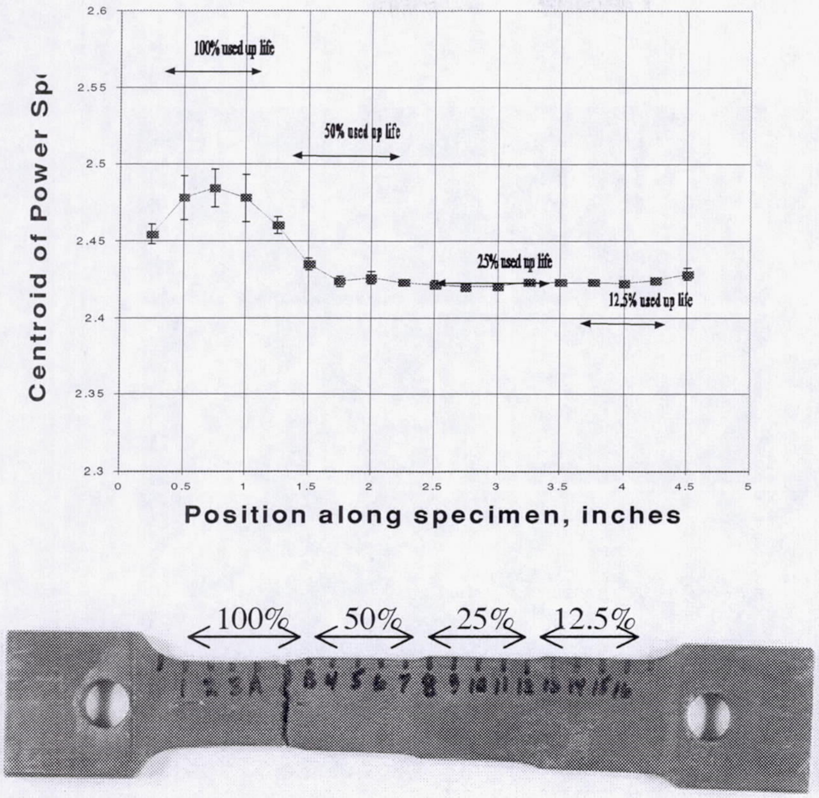


Fig.3- Acousto ultrasonic measurements along profile of the stepped creep specimen (75.7 ksi 1350 F and 260 hrs). Indicated are percentages of used-up life.

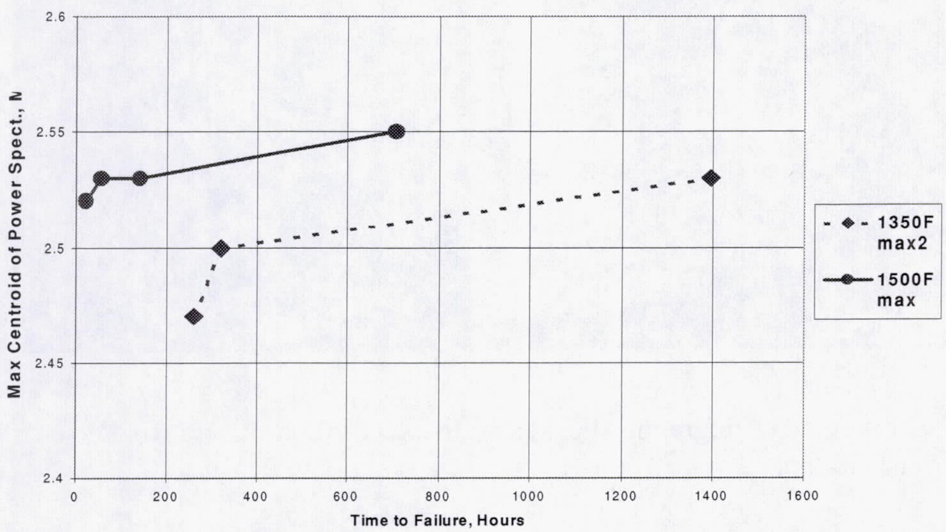


Fig.4- Maximum AU values increase with specimen lives

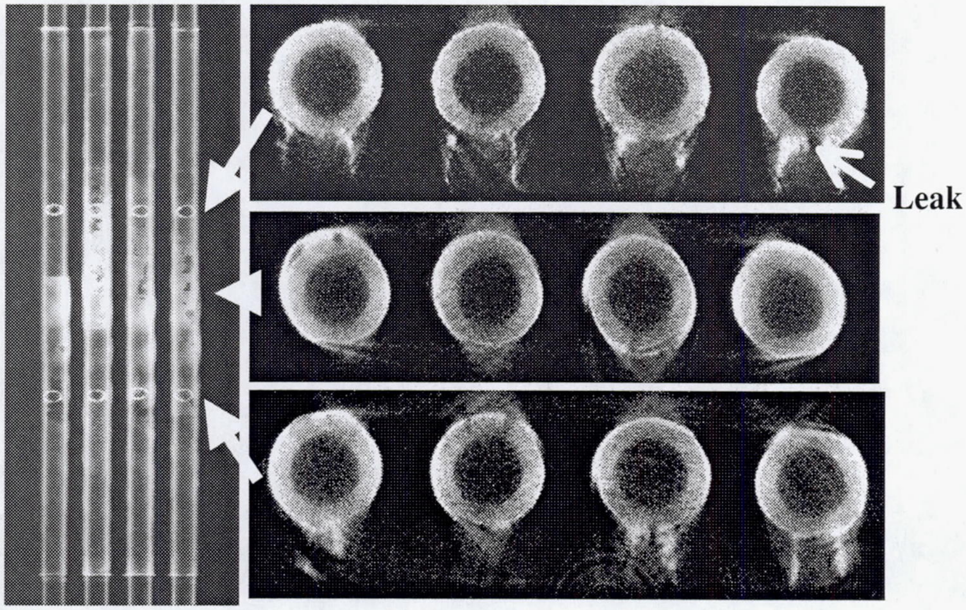


Fig.5- X-ray and three computed tomography slices of the composite panel.

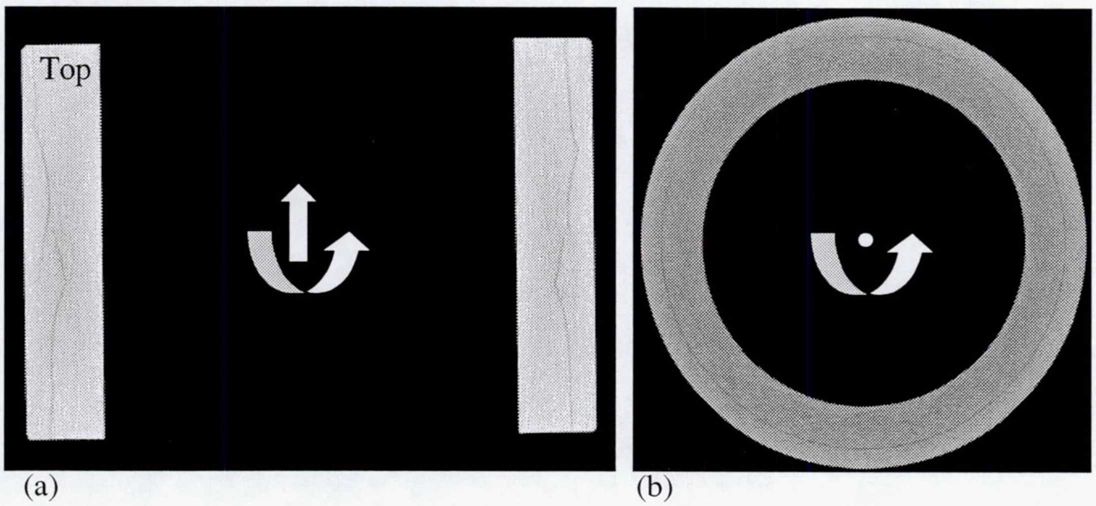
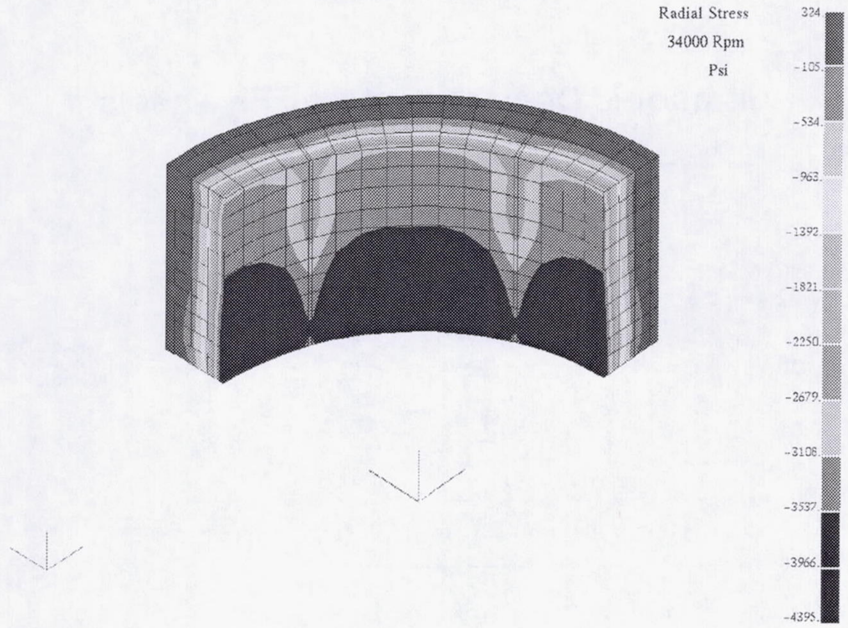
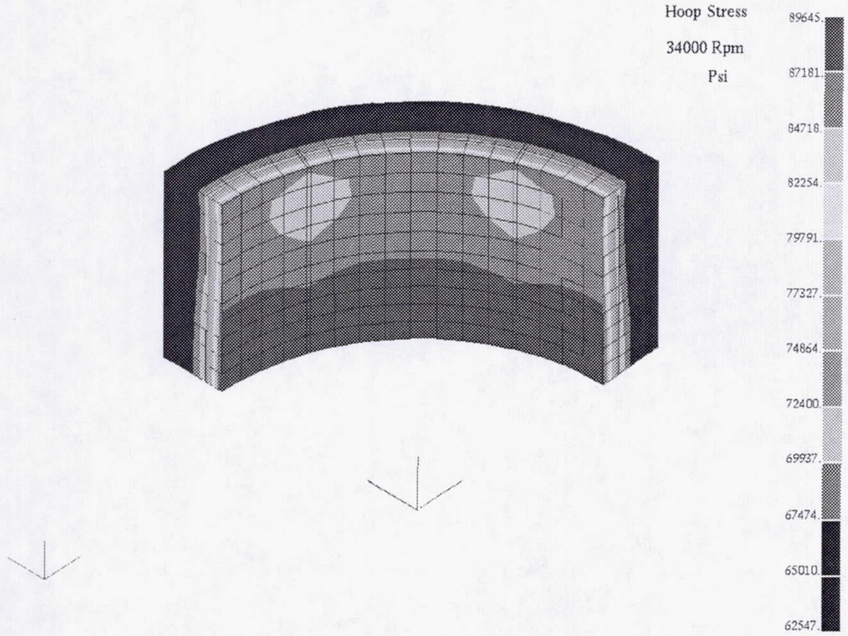


Fig.6- X-ray computed tomography slices (a) // to axis of rotation and (b) $\perp$ to axis of rotation near the top.



(a)



(b)

Fig. 7 - 3D radial (a) and hoop (b) stress distributions explain the different paths of the crack along the axial direction as shown in Fig. 6a.

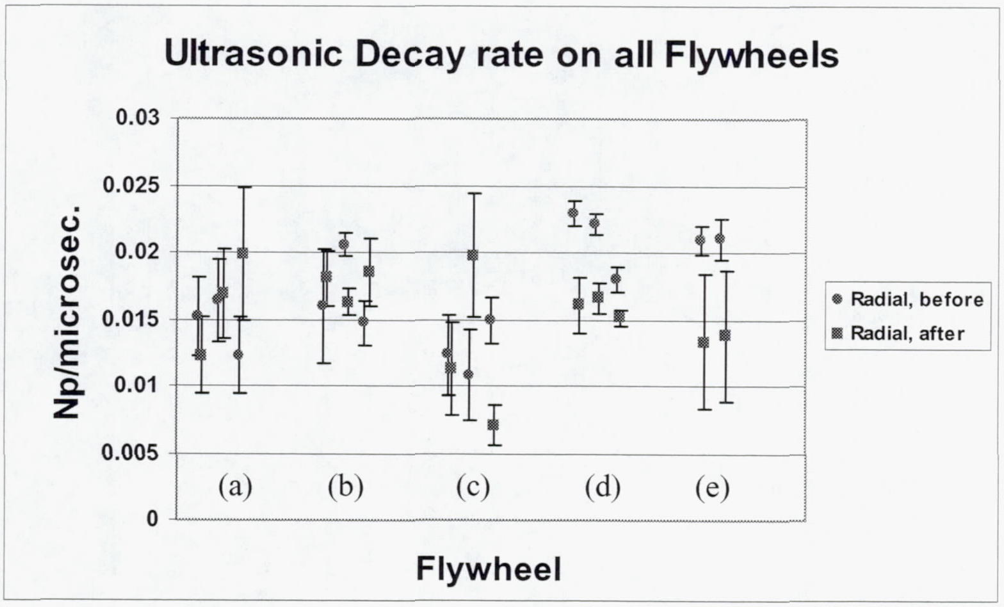


Fig. 8 - Acousto ultrasonic decay rates classify flywheels before and after spin testing only for relatively optimized materials like (d) and (e).

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13. ABSTRACT ***(Maximum 200 words)***

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