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NDE Methodologies for Composite Flywheels Certification

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ABSTRACT

Manufacturing readiness of composite rotors and certification of flywheels depend in part on the maturity of nondestructive evaluation (NDE) technology for process optimization and quality assurance, respectively. Capabilities and limitations of x-ray-computed tomography and radiography, as well as advanced ultrasonics were established on NDE ring and rotor standards with EDM notches and drilled holes. Also, intentionally seeded delamination, tow break, and insert of bagging material were introduced in hydroburst-rings to study the NDE detection capabilities of such anomalies and their effect on the damage tolerance and safe life margins of subscale rings and rotors. Examples of possible occurring flaws or anomalies in composite rings as detected by NDE and validated by destructive metallography are shown. The general NDE approach to ensure quality of composite rotors and to help in the certification of flywheels is briefly outlined.

INTRODUCTION

The flywheel technology for energy storage systems is gaining broader support, more than it did for the last 25 years [1-4], because of current support from NASA and U.S. Air Force space programs. The drive is not only to improve energy storage systems where the state of charge can be known but also to concurrently perform attitude control depending on the specific application for a given spacecraft [5]. Some of the major challenges in the flywheel technology for the international space station (ISS) include high-speed rotors and carbon reinforced composite materials that can meet the safe-life design requirements, reliability and durability to end-of-life, flight certification, and safety constraints while delivering the high energy density needed [6]. In this paper, the research is limited to the NDE of composite flywheel rotors and rings that are targeted under the flywheel energy storage system (FESS) program [7]. These composite rotors are to be flown on the ISS replacing a battery charge/discharge unit.

MATERIALS AND NDE METHODS AND STANDARDS

The composite materials under investigation, the NDE methods employed, and the NDE standards are all described in the following sections:

MATERIALS - Composite flywheel rings and rotors were fabricated using proprietary materials and processes. The composite material system consists of polymer matrix composites (PMCs), using toughened resin systems, with added features to enhance fracture toughness for the laminate and prevent/mitigate the formation of cracks. This fabrication process is autoclave based, to assist with consolidation and to reduce void content.

The flywheel, see Fig.1, consists of a solid cylindrical composite energy storage unit made of concentric rings press fit (preloaded) together, operating with a rotor tip speed approximately 835 m/s.

NDE METHODS - Several ultrasonic methods were used for the material characterization of the composite rotors. Through-transmission (TT) and pulse-echo (PE) methodologies were used for flaw detection and acousto-ultrasonics (AU) and ultrasonic spectroscopy (US) were used for degradation and damage assessment before and after fatigue or burst tests. In this paper we limit our discussion to the TT and PE ultrasonic scanning methods suitable for flaw detection. Several x-ray methods were used like conventional and microfocus radiography and 420 KeV and 3 MeV computed tomography (CT). Conventional and microfocus radiography were used for flaw detection and composite architecture verification. Low energy CT, 420 KeV, was used for thin rings and thin-rim rotors whereas high energy CT, 2-3 MeV, was used for thick composite rings and thick-rim rotors with hubs. Conventional and microfocus radiography were used in the 40 to 80 KeV and 5 mA to 0.4mA, respectively.

Pulse Echo and Through Transmission Ultrasonics - Figure 2 shows the immersion ultrasonic scanning system during a PE inspection of one composite ring. PE is an ultrasonic method in which only one transducer is used to send the sound into the material and then to receive the sound after it bounces off the back surface of the object under inspection. TT is an ultrasonic method in which two transducers are used, one to send the sound from one side into the object under investigation, and a second transducer to receive the sound after it traversed the object. This method requires access to both front (OD) and back (ID) surfaces of objects like composite rings and rotors without a metallic hub. PE method is better suited for the evaluation of an object with one side access similar to the case of a composite rotor with a hub. Both TT and PE methods provide information on the internal state of the material by studying the attenuation mechanisms that take place during the traverse of sound through the material.

X-ray Computed Tomography and Radiography - Figure 3 shows a schematic of x-ray computed tomography setup where the object under inspection is rotated at small increment angles, 0.2 degree, collecting many projections from the x-ray fan beam after it attenuates through the object and is received at the detector. These projections are then built in the Fourier domain allowing fast inverse Fourier algorithms to be utilized for reconstructing the CT cross-section, called the CT slice, information at a specific location or height. The CT slice reveals internal mass attenuation coefficient differences due to the presence of different material compositions or features. These differences can be attributed to and correlated with density differences between material constituents. X-ray radiography on the other hand, a simpler imaging method than CT, uses the same principle of x-ray attenuation. In conventional and microfocus radiography the x-ray beam is in general conical in shape as opposed to the fan shape in CT, and the resulting image/radiograph is a 2D shadowgram that superimpose all information in the x-ray path. In microfocus radiography, the spatial resolution and contrast sensitivity are improved by comparison to conventional radiography because the focal spot size of the microfocus x-ray tube is on the order of 5-50 μm whereas that of a conventional tube is 400 μm and above. Also, the projection mode in microfocus radiography reduces the scattered radiation which normally deteriorate the signal to noise ratio in the direct-contact conventional-radiography mode.

NDE STANDARDS - The NDE standards were made to establish the capabilities and limitations of the NDE methods employed, and to use them as NDE reference standards to ensure that the NDE methods employed were performing to specifications every time they were used.

Composite Ring Standard - Figure 4 is a schematic of a typical ring standard with EDM notches ranging from 125x125 μm to 750x1500 μm (5x5 mils to 30x60 mils) and drilled holes ranging from 300μm to 1600μm (12 mil to 1/16") in diameter. These notches and drilled holes were 12.5 mm (1/2") deep in a 12.5 mm (1/2") wide by 12.5 mm (1/2") high composite ring.

Composite Rotor Standard - Figure 5 is a CT slice of a multi-layered rotor standard. The hub is made of Ti-6Al-4V and the rim is a multi-layered PMC. The same set of EDM notches and drilled holes (125x125 μm, 300 μm, 390 μm, 500x500 μm, 780 μm, and 750x1500 μm) was machined into each of the eight composite layers. The set was duplicated in a spiral fashion starting at the innermost ring at the ID to the outermost one at the OD.

RESULTS AND DISCUSSION

Ring Standard - Table I shows all the NDE findings taken on two standard rings by using ultrasonic TT and PE methods, conventional as well as microfocus radiography and 420KeV and 3 MeV x-ray CT methods. The microfocus radiography images of one of the standard ring are shown in figure 6. The ultrasonic images are shown in figures 7 and 8. From table I findings and figure 6 images microfocus radiography was demonstrated to be a viable NDE technique to detect EDM notches and drilled holes down to a 125x125 μm notch and 300 μm drilled hole. Conventional radiography was capable of detecting EDM notches down to 250x750 μm and drilled holes down to 780 μm in diameter. However, conventional radiography is capable of detecting metallic inclusion down to 125x125 μm. Computed tomography findings demonstrate that EDM notches down to 125x125 μm and drilled holes down to 300 μm in diameter can be easily detected by 420KeV as well as by a 3 MeV systems. The PE ultrasonic method was found to be capable of detecting EDM notches down to 125x125 μm and drilled holes down to 300 μm in diameter. TT method was capable of detecting EDM notches down to 125x1000 μm and drilled holes down to 780 μm in diameter.

Rotor Standard - All EDM notches and drilled holes were detected in all composite layers by using 3MeV CT. The selected CT slice shown in figure 5 substantiates the finding. This is a major result for high energy CT to detect low-density flaw down to 125x125 μm in a thick-rim rotor. This further demonstrates that x-ray CT can play a major role in rotor flight certification. Ultrasonic scanning results, not shown herein because of space limitation, demonstrated 1) penetration capabilities of 4.5 cm and detection capabilities down to 750x1500 μm (30x60 mils) in the outermost ring only for the case of 1 MHz, 2) penetration capabilities of 2 cm and detection capabilities of the whole set in the outermost ring and down to 500x500 μm (20x20 mils) in the second ring from the OD at 2.25 MHz, and 3) penetration capabilities of 2 cm and detection capabilities of the whole set in the first two ring from the OD.

Seeded Delamination and Bagging Materials - A delamination was created in one hydroburst ring that spans 180 degrees of the circumference at midpoint in the radial direction. An optical photograph of a selected section of the delamination is shown in figure 9 where the schematic of propagating ultrasound bouncing off the I.D. surface of the ring is also depicted. The time domain of the ultrasound signal highlights the presence of the delamination, second peak, between the front surface reflection, peak 1, and back surface reflection, peak 3. Gating the second peak in the time domain, the delamination, resulted in imaging the presence of the delamination (echo coming from the wall/interface created by the delamination) between 180° and 0° (clock wise) as shown in the top of figure 9.

Figure 10 shows the ultrasonic PE scan of the hydroburst ring with seeded insert of bagging material located at 120 degree in the middle of the 4 mm thick by 12.7 mm wide ring. The insert was easily detected by PE ultrasonics and is depicted as a black line at the 120 °-angle location at the top of figure 10. The tow-break was simulated by an EDM notch on the ID surface of a hydroburst ring. The notches were easily detected because they were comparable to the larger EDM notches imaged in the ring standard as shown previously in figures 6-8 and Table I.

Examples of Possible Occurring Flaws - Figure 11 shows a large delamination in one of the rings as detected by PE ultrasonic method. This delamination spans a 54-degree angle near the bottom edge, and is 15 cm in height. The optical photograph of a section of the ring as exposed to the surface shows clear evidence of that delamination in figure 12. Figure 13 shows a sizeable void, about 1x2 mm (40x80 mils), at the glass-composite interface as detected by x-ray CT. The glass layer was machined off and the low-density feature as detected by CT was demonstrated to be a void. A selected area from a CT slice of a composite ring is shown in figure 14(a). The dark region, lower-density feature near the I.D., depicts the presence of a resin rich area. After the ring was sectioned destructively and the specific location was exposed to the surface and polished, the optical photograph (Fig. 14b) confirms the CT findings of the resin rich area.

General NDE Approach Toward Flywheel Certification - The current NDE plan, to ensure quality of composite rotors and to help in the certification of flywheels, based on the findings in this work is to 1) perform flaw/damage detection on 100% of the rings with P-E ultrasonics and real-time microfocus radiography and selected slices with computed tomography, 2) perform flaw/damage detection on 100% of the rotor with thick computed tomography slices and 100% of the outer shells with 5MHz P-E ultrasonics down to 2 cm deep from the OD of the rotor, and 3) perform general c-scan evaluation with 0.5 MHz P-E ultrasonics down to 4.5 cm deep from the OD of the rotor. Further, based on work by Baaklini et.al., [8], and by Harmon and Baaklini [9] not reported herein, NDE for material characterization and degradation assessment of mechanical properties and interfaces is to be performed on 100% of the rotors via acousto-ultrasonics and ultrasonic resonance spectroscopy.

CONCLUSION

Capabilities and limitations of x-ray-computed tomography and radiography, as well as advanced ultrasonics were established on nondestructive evaluation (NDE) ring and rotor standards with EDM notches and drilled holes. EDM notches down to 125 by 125 μm and drilled holes down to 300 μm in diameter were detected in a thick multi-layered rotor by using x-ray computed tomography. At the ring level, x-ray microfocus radiography, x-ray computed tomography, and pulse echo ultrasonic scans were able to detect EDM notches down to 125 by 125 μm and drilled holes down to 300 μm in diameter. Intentionally seeded delamination, tow break, and insert of bagging material were easily detected in hydroburst rings by using the ultrasonic pulse echo method. Possible occurring anomalies like delamination in polymer matrix composite layers, void in glass layers, and resin rich regions in the composite layers, were all detected by NDE and verified by metallography. The general NDE approach to ensure quality of composite rotors and to help in the certification of flywheels was briefly outlined.

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	Standard ring #1					Standard ring #2			
Defect Size µm	UT TT	RT C	RT M	CT 420 KeV	CT 3 MeV	UT PE	RT M	CT 420 KeV	CT 3 MeV
125x125	-	hd	x	-	x	x	x	x	x
125x500	-	-	x	x	-	x	x	x	x
125x750	-	-	x	x	x	x	x	x	x
125x1000	x	-	x	x	x	x	x	x	x
250x250	x	-	x	x	x	x	x	x	x
250x500	x	hd	x	x	x	x	x	x	x
250x750	x	x	x	x	x	x	x	x	x
250x1000	x	x	x	x	x	x	x	x	x
500x500	x	x	x	x	x	x	x	x	x
500x1500	x	x	x	x	x	x	x	x	x
750x750	x	x	x	x	x	x	x	x	x
750x1500	x	x	x	x	x	x	x	x	x
390	-	-	x	x	x	x	x	x	x
780	x	x	x	x	x	x	x	x	x
Cluster of 390	x	x	x	x	x	x	x	x	x
Cluster of 780	x	x	x	x	x	x	x	x	x
300	-	hd	x	x	x	x	x	x	x
1170	x	x	x	x	x	x	x	x	x
1560	x	x	x	x	x	x	x	x	x

Table I. - NDE detection capabilities of EDM notches and drilled holes in standard ring #1 and standard ring #2. (hd is short for high density broken metallic EDM wire; UT is ultrasonic testing; TT is through transmission; PE is pulse echo; RT is radiographic testing; C is conventional; M is microfocus; CT is computed tomography

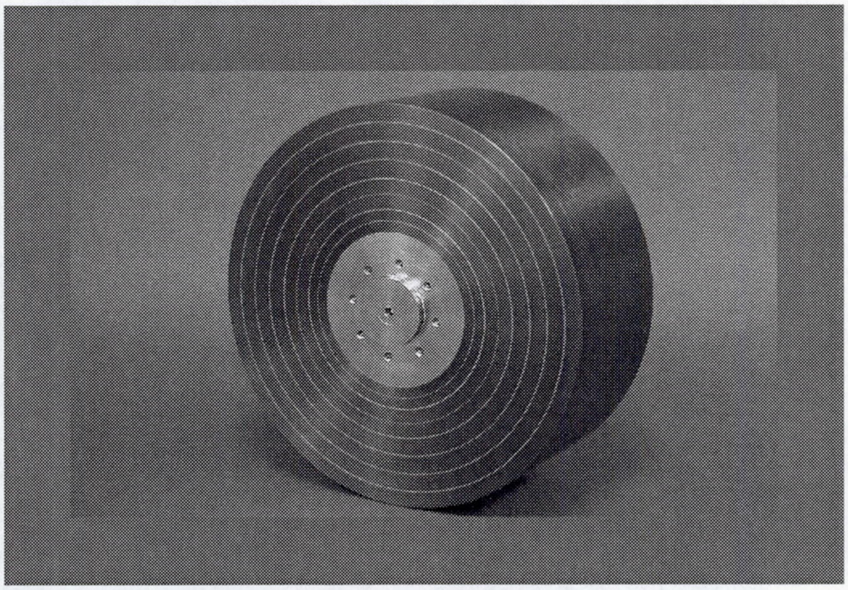

Fig. 1- Preloaded composite rotor for the flywheel energy storage system targeting the replacement of chemical batteries on the international space station

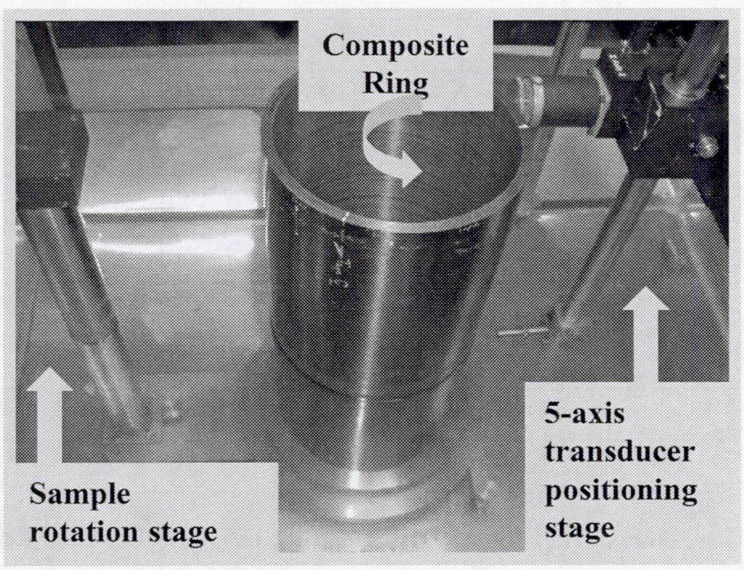

Fig. 2.- Immersion ultrasonic scanning system as applied to composite ring evaluation

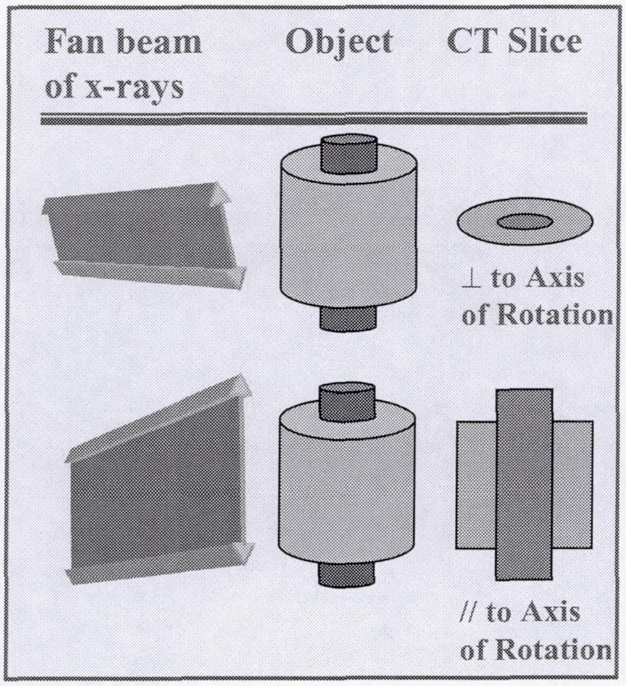

Fig. 3.- Schematic of x-ray computed tomography as applied to composite rotor evaluation

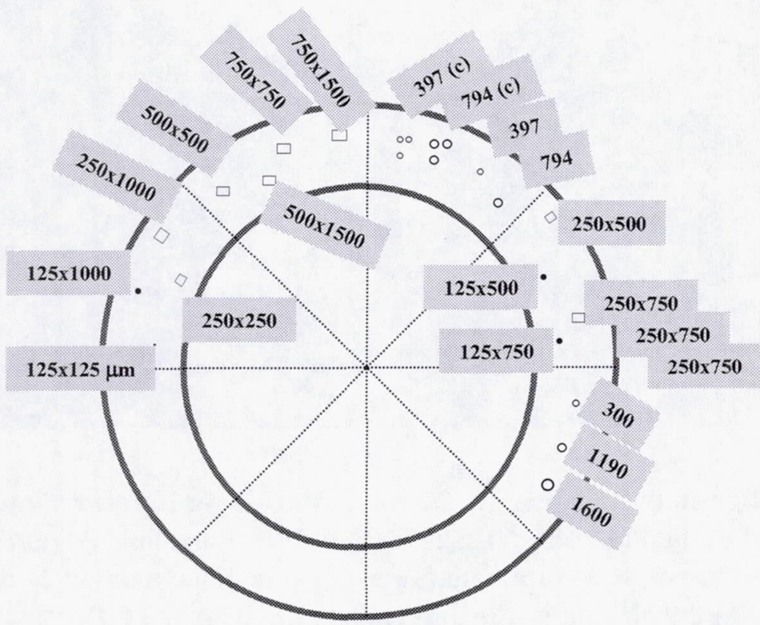

Fig. 4- Schematic of a nondestructive evaluation ring standard with EDM notches and drilled holes. Ring is 12.5 mm high and 12.5 mm thick, and notches and holes are 6.25 mm deep. Measurements shown on figure are in micrometers and the schematic is not to scale. C in 397 (c) stands for cluster of 397 μm drilled holes.

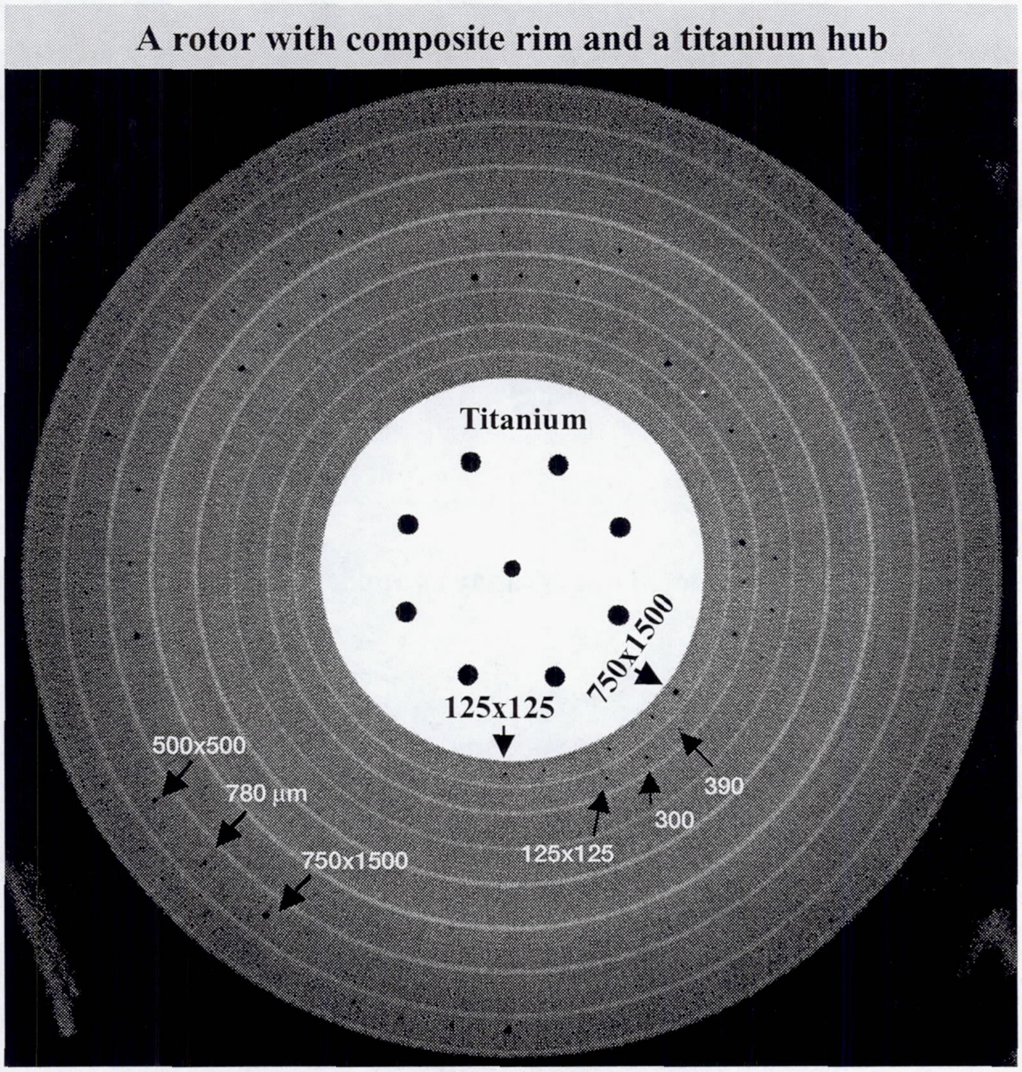

Fig. 5 - Computed tomography slice of a multi-layered rotor standard with EDM notches and drilled holes set (125x125, 300, 390, 500x500, 780, and 750x1500 µm) in each layer. This set was duplicated in a spiral fashion starting at the innermost ring near the ID and finishing at the outermost ring near the OD.

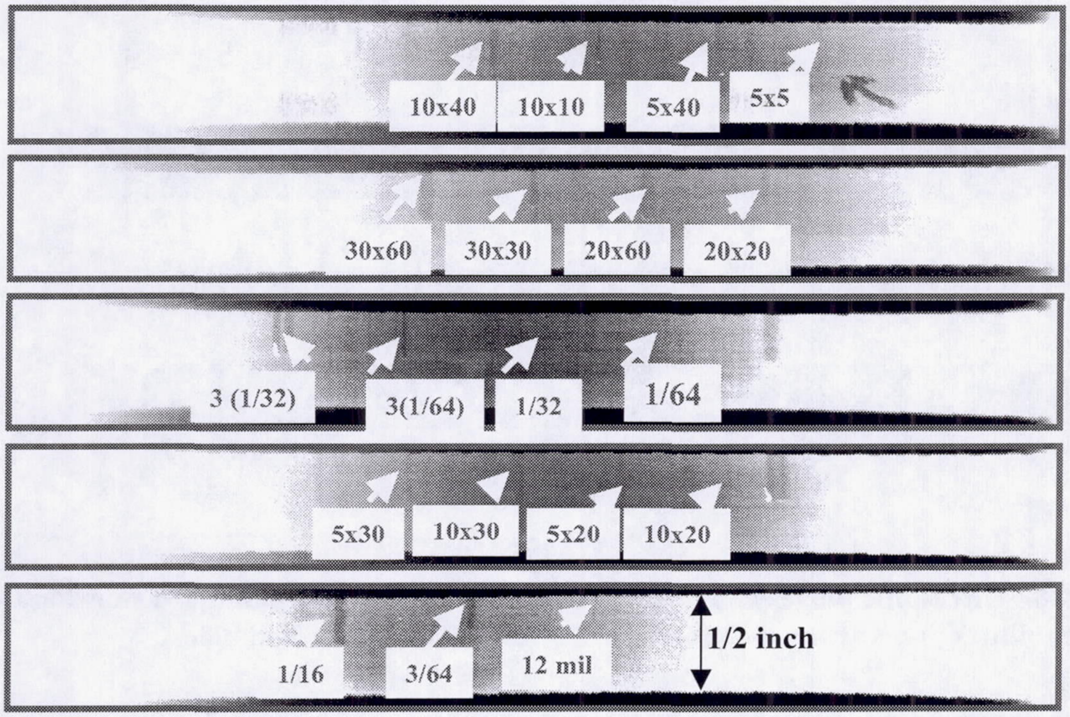

Fig. 6 - Microfocus radiography of one NDE ring standard showing the capabilities of detection down to 125x125 μm (5x5 mils) notch. Measurements shown are in mils and images shown are prints of 5 radiographs taken in direct contact with the ID of the ring.

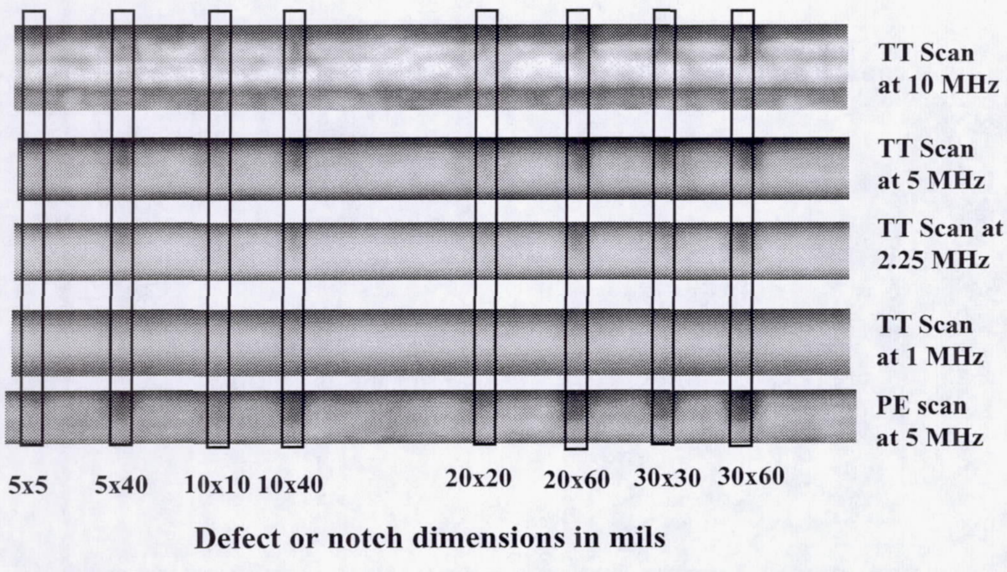

Fig. 7 - Ultrasonic scanning of one NDE ring standard showing the capabilities of detection with through transmission (TT) and pulse echo (PE) methods. The scans of the ring as displayed are open cylinders (rectangles) where the vertical direction represents the height of the ring and the horizontal direction represents the circumference from 0-359 degrees.

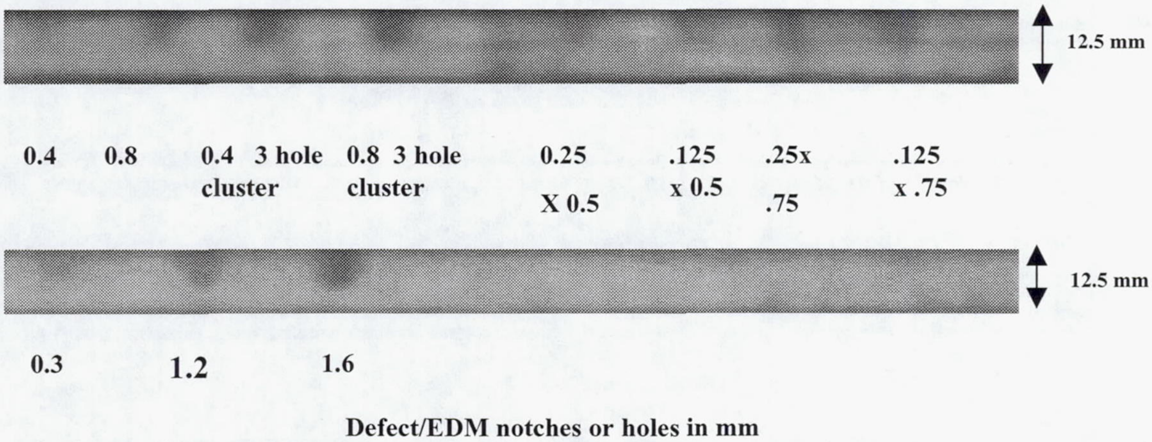

Fig. 8- Ultrasonic pulse echo (5MHz) scans of one NDE ring standard showing the capabilities of detecting 6.5mm deep EDM notches and drilled holes

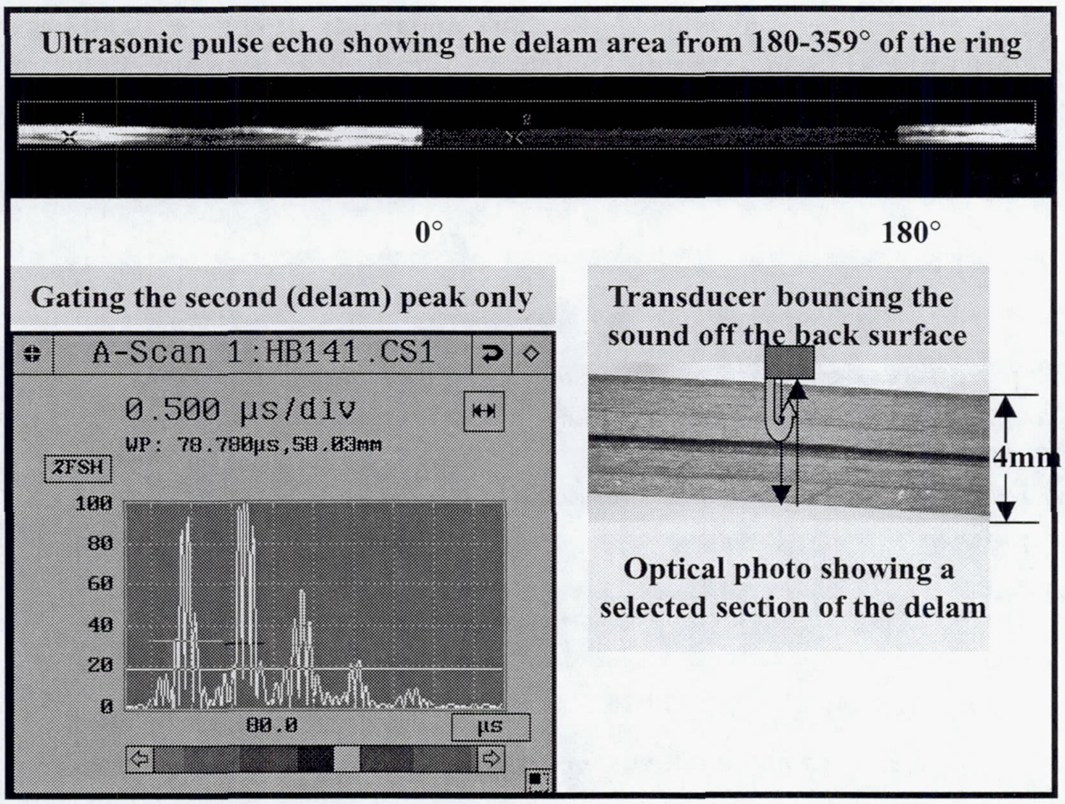

Fig. 9- Immersion pulse echo ultrasonic scan of a 180 ° delam in a hydroburst ring

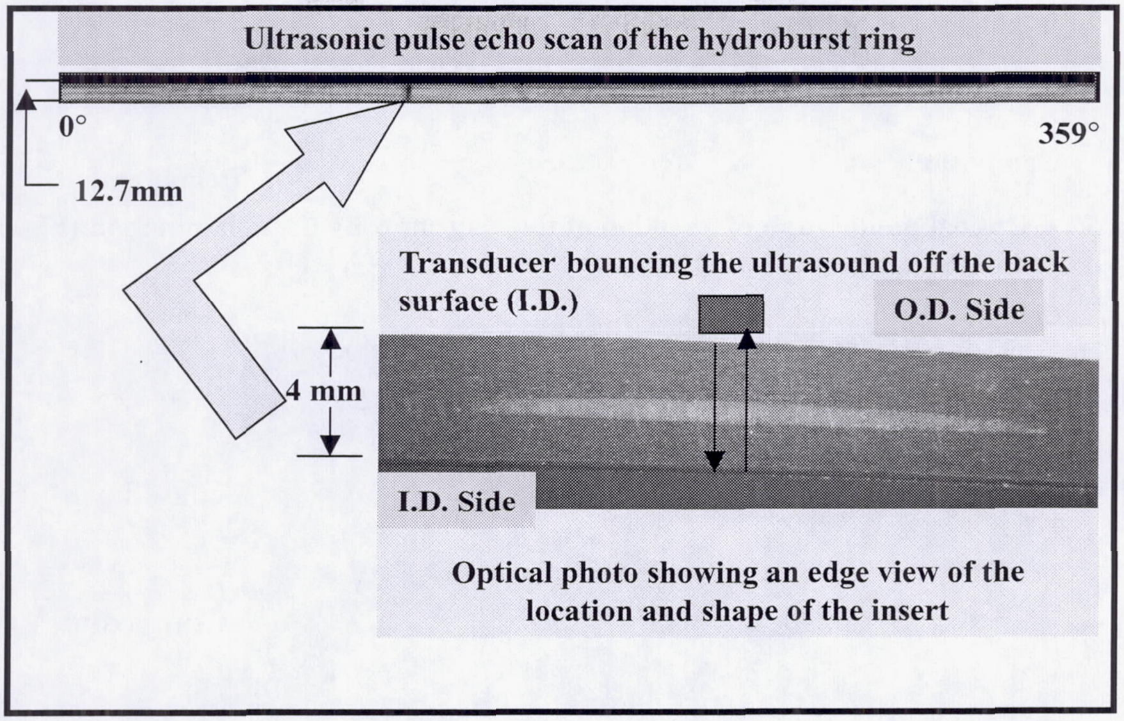

Fig. 10- Immersion ultrasonic pulse echo scan detects the insert of bagging material in a hydroburst ring

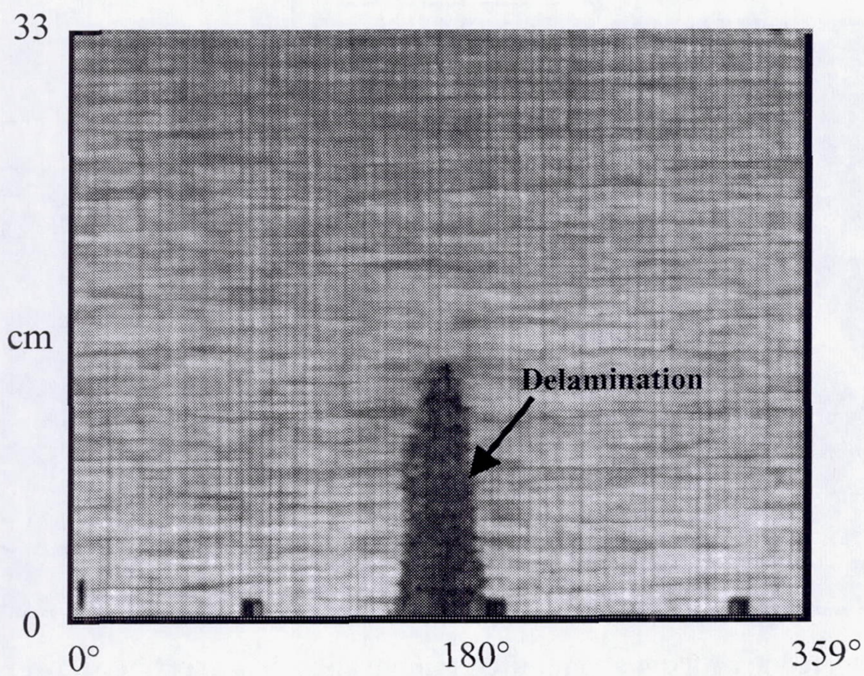

Fig. 11 - Ultrasonic scan showing a large delamination in one of the rings

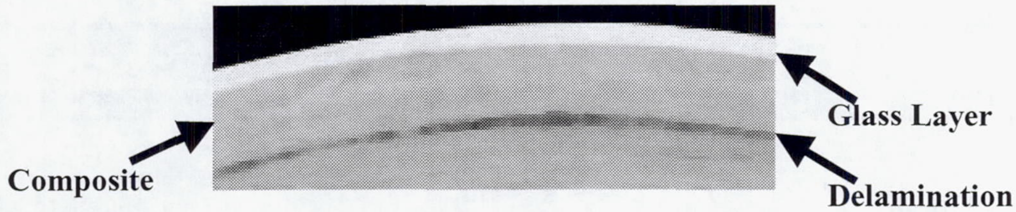

Fig. 12 - Optical photograph of a section of the ring showing the delamination (Fig. 11) as exposed to the surface

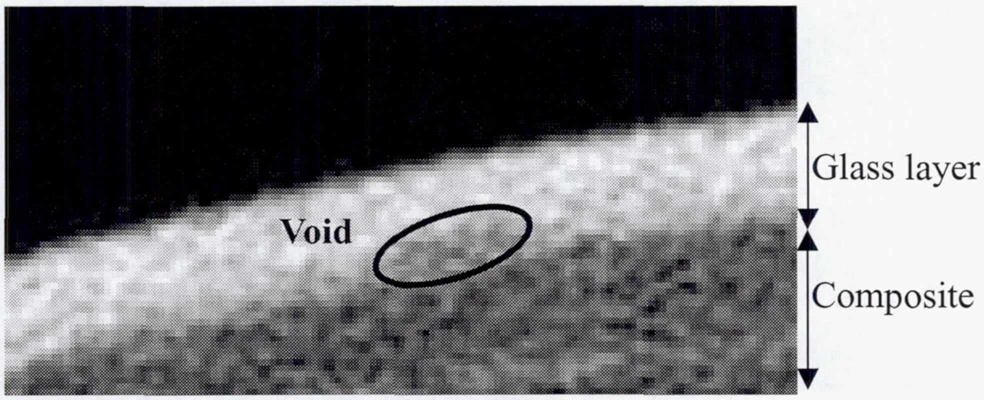

Fig. 13 - Selected section from the CT scan showing a 40x80 mils void in the glass layer

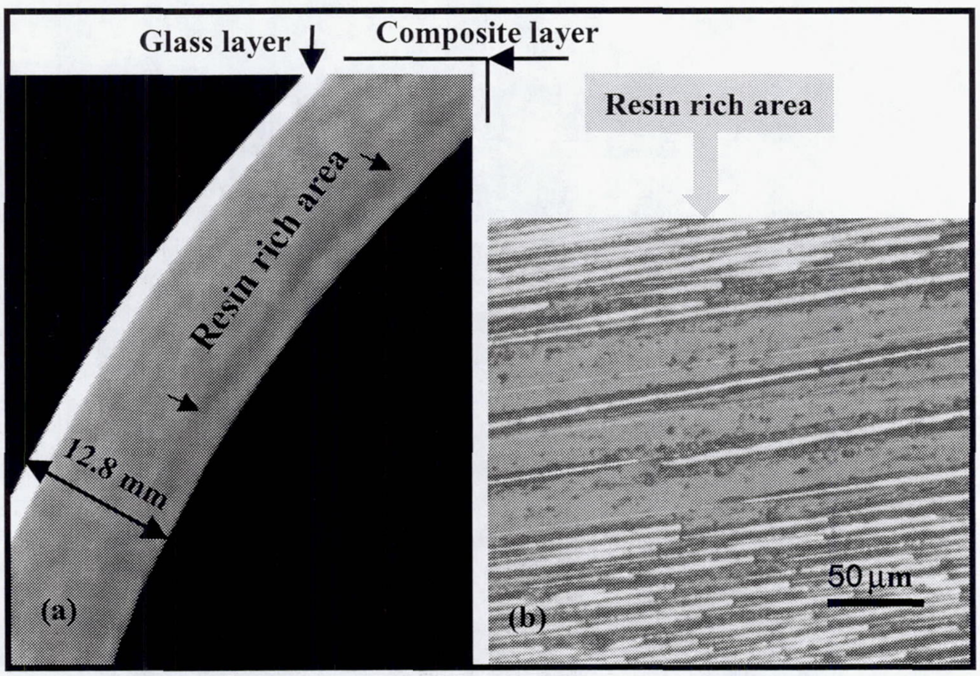

Fig. 14- Selected area from a computed tomography cross section showing a resin rich region within the composite layer (a), and an optical photograph of the resin rich region after destructive sectioning and polishing for validation (b)

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

Manufacturing readiness of composite rotors and certification of flywheels depend in part on the maturity of nondestructive evaluation (NDE) technology for process optimization and quality assurance, respectively. Capabilities and limitations of x-ray-computed tomography and radiography, as well as advanced ultrasonics were established on NDE ring and rotor standards with EDM notches and drilled holes. Also, intentionally seeded delamination, tow break, and insert of bagging material were introduced in hydroburst-rings to study the NDE detection capabilities of such anomalies and their effect on the damage tolerance and safe life margins of subscale rings and rotors. Examples of possible occurring flaws or anomalies in composite rings as detected by NDE and validated by destructive metallography are shown. The general NDE approach to ensure quality of composite rotors and to help in the certification of flywheels is briefly outlined.

14. SUBJECT TERMS

NDE; Composites; Flywheels; Radiography; Ultrasonics; Computed tomography; Composite rotors; Flight certification

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