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Assessment of Nondestructive Evaluation Methods for Hoop-Wrapped Cylinders

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Disclaimer

INTRODUCTION:

Catastrophic ruptures and leaks have recently occurred in high pressure cylinders used as air-breathing apparatus. These failures have all occurred in fiberglass wrapped seamless-aluminum cylinders which have a designed service pressure of 4500 psi. The cylinders experiencing leaks or ruptures are designed as hoop wrapped cylinders in which the fiberglass is wrapped only over the body of the cylinder and the neck and head is left unwrapped due to the lower stresses present in the head and neck of the cylinder. All cylinders are fabricated of aluminum alloy type 6351 heat treated to the T-6 temper condition (solution treated and aged).

The cylinders in which leaks and ruptures have occurred are manufactured to specifications given by the U.S. Department of Tranportation (DOT) exemption number DOT-E-7235. The present work was undertaken by NBS at the request of the DOT to determine if a suitable nondestructive evaluation procedure could be developed to identify cylinders containing cracks and to remove these cylinders from service prior to failure.

The particular mode of failure shown in these cylinders first occurred in cylinders made from alloy 6351 which contained higher than normal levels of impurities such as lead (Pb) and bismuth (Bi). A maximum level of 0.05% of Pb and Bi is permitted in alloy 6351, although the normal level of these elements is approximately 0.01%. In the first cylinders in which rupture and leaking was observed, the level of Pb and Bi approached 0.05%.

The ruptures and leaks observed in these cylinders were caused by cracks in the threads in the neck of the cylinder. The cracks were oriented parallel to the longitudinal axis of the cylinder and started from interior of the cylinder at the point where the lowest thread intersected the neck of the cylinder. Both single and multiple cracks (usually located 180° apart) were observed. The cracks propagated through the cylinder neck in an intergranular mode. The cracking occurs over time when the cylinder is stressed due to the internal gas pressure and is believed to be a stress-time phenomena due to a form of creep cracking mechanism.

As a result of the rupture of two cylinders and the leaking of several others, the following steps have been taken to reduce the occurence of failures and to increase the probability that any failures will be leaks rather than catastrophic ruptures:

1. The service pressure has been reduced from 4500 psi to 4000 psi.
2. Visual inspection of the threaded necks of all cylinders is being performed.
3. Manufacture of new cylinders has been suspended except for the manufacture of a limited number as replacements for those removed from service due to cracking. These new cylinders must be fabricated from alloy 6351 containing less than 0.01% of Pb and Bi.

In addition an extensive research and development program has been initiated to: 1) determine the cause of failure through analysis; 2) determine the mechanism of cracking through controlled laboratory tests; 3) modify the shape of the cylinder head to reduce the stress level in the neck; 4) modify the manufacturing process for forming the cylinder heads to produce an improved microstructure in the head; and 5) design a "neck ring" which can be retrofitted to the cylinder to cause failure by leaking instead of by rupture.

In order to permit the cylinders presently in service to continue to be used and at the same time to reduce the probability of catastrophic rupture, the need for a suitable and reliable nondestructive inspection procedure became apparent. A reliable nondestructive evaluation (NDE) procedure is required for the following reasons:

1. To immediately inspect all existing cylinders and remove from service any containing existing cracks;
2. To provide a method for periodic reinspection of cylinders in the future to locate any cracks which develop during service, and
3. To inspect existing cylinders and remove any containing cracks before retrofitting "neck rings" to permit the service pressure to be raised back to 4500 psi from the presently restricted 4000 psi.

The requirements for an acceptable NDE procedure were determined to be the following:

1. All cracks larger than a specified minimum size must be located.
   As an initial acceptance level a crack size that has a depth equal to the crest to root depth of the thread and a length equal to the distance between the crest of two threads was chosen as the minimum size that the NDE procedure should be able to locate;
2. A minimum number of "false readings" should occur due to seams and folds, threads, or noise from the NDE instrumentation;
3. No contamination of the cylinder should occur that would require special cleaning before the cylinder could be refilled with breathable quality air;
4. The NDE procedure should be readily usable under field conditions such as cylinder retest or refill facilities;
5. The inspection cost should be moderate relative to the initial cost of the cylinder;
6. Reliable results should be obtained with minimal inspector training and the NDE procedure should be relatively insensitive to variations

by different inspectors;

7. Currently available, commercial NDE equipment must be used with a minimal amount of adaptation or optimization of the equipment; and
8. It is desirable to be able to determine the approximate size (length and depth) of any cracks found.

General Description of Non Destructive Evaluation Methods

Several nondestructive evaluation (NDE) methods (1) were considered for this application and, for most of these, preliminary tests were made to determine feasibility. The methods that appeared feasible included the following: visual/optical liquid penetrant, radiographic, eddy current, ultrasonic and acoustic emission.

The visual/optical methods has the virtue of simplicity. The methods depend on the changing reflection of light from a sound and a cracked surface. There are difficulties in getting light into the small cylinder neck while leaving room for an observer to look at the threaded walls. Small, directed light sources, angled magnifying mirrors and borescopes that can provide a light and visualization path in one assembly by the use of fiber optics appear useful for this application.

The liquid penetrant method (2) was considered in conjunction with the visual/optical approach since penetrants are used to improve the visibility of surface defects such as cracks. The method depends on liquids that will readily enter a surface opening when put on the material to be tested. The liquids contain a dye (either a high contrast visual dye or a dye that fluoresces upon ultraviolet excitation; the latter is a fluorescent penetrant). When the material surface is cleaned of excess penetrant only the dye-containing liquid in the discontinuities remains. This is drawn up to the surface by the blotting action of a developer to yield an enlarged and high contrast visual indication of the discontinuity. Penetrants appeared useful for this application because improved visibility of cracks would result. However, dye penetrants have the disadvantage that any residue from the penetrant may contaminate the cylinder.

Radiography (3,4) indicates discontinuities by the changing radiation transmission through volumes that differ in density. An opening, such as a crack, will transmit more radiation than solid material. This difference in transmitted radiation is normally detected with radiographic film. Possibilities for radiography included (1) placing the source outside the cylinder and shooting across the threaded opening to a film around the back side of the threaded neck, (2) placing a source inside the threaded neck and making a panoramic radiographic exposure to film wrapped around the outside of the threaded neck and (3) placing the source outside and shooting along the cylinder axis from bottom to top to a film perpendicular to the radiation beam (along the cylinder axis) at the threaded end. Option 1 would require several exposures to detect radially-oriented cracks since the radiation beam must be reasonably oriented with the crack. Option 2 would yield a result with a single film exposure but would require the use of an extremely small focal spot radiation source in order to provide a radiograph with sufficient resolution to observe cracks. Option 3 would yield a result with a single film exposure. The radially-oriented cracks expected tend to be parallel to the axis so radiography in this mode should show the cracks.

Eddy currents (5,6) are well suited for the detection of surface and near-surface discontinuities in metallic (electrically conducting) materials. A varying magnetic field interrogates the material, creating circulating electrical currents in the material. A discontinuity will perturb the current flow and cause a change in the magnetic field the current creates. These changes can be detected by detectors such as coils or Hall probes. For this problem, it will be necessary to place the interrogating coil and detector (which are often the same coil) close to the material surfaces in the threads and at a consistent distance in order to minimize signal variations due to a changing distance between coil and material (known as a lift-off effect). Embedding an eddy current coil in a threaded bolt that can be turned through the threads appears attractive.

Ultrasonic methods (7) involve the use of high frequency acoustic energy to interrogate material. The ultrasonic wave is changed as it encounters a discontinuity in the material. Cracks in metals present a significant change in accoustic impedance and a large part of the ultrasonic energy striking an interface or a crack is reflected. Detection of this signal - or the change in the transmitted signal - is indicative of a discontinuity in the material. Since ultrasonic methods are particularly useful for crack detection, this technique must be considered for this application. However, the close proximity of the threads to the region being inspected, the changing thickness and curvature of the cylinder and the large grain structure present problem areas. Ultrasonic signals will be received from the threads making it difficult to observe a defect in that region. The surface curvature makes it difficult to couple the ultrasonic signal into the material and to locate a receiving transducer to detect the return signal. The large grain structure approaches the size of the ultrasonic wave-length and leads to high attenuation of the signal and confusion due to the scattering from the grains themselves.

In acoustic emission testing (8,9) one tries to detect stress waves emitted from a propagating defect. A stress is necessary so the material under test should be subjected to stress due to pressure, mechanical or other means. This approach is attractive for the cylinder problem because one can visualize a test in which one "listens" to the cylinder as it is being pressurized. Typically in acoustic emission several transducers are used so the source of the emission can be located by triangulation. In principle this is possible in the case of the gas cylinders but one would have to locate series of transducers around the diameter. Further, the stress waves emitted from a growing crack in the neck would be subject to multiple reflections from the threads and walls. There are also strong possibilities for stress wave emissions due to breaking of the filaments around the body of these filament-wound cylinders and from movements of the pressure valve in the threads. One can, therefore, expect signals from several sources. This, along with the fact that aluminum usually yields relatively low intensity acoustic emission signals, will tend to complicate the situation.

NBS EXPERIMENTAL RESULTS:

Optical/Visual Methods:

1. Dentist Mirror - 1x with lighting by Burtron micro light set

   Procedure described below was followed: major cracks rarely found even by experienced inspector.

2. Dentist Mirror - 2x with lighting by Burtron micro light set

   a. Tested: full cylinders
      cracked
      uncracked

   b. Cleaning prior to examination
      ultrasonic bath with solvent
      to remove oil/grease/dirt

   c. Inspection procedure:
      darken room
      manually inspect with mirror and light

   d. Results:
      Operator skill/experience:

      At least three people examined each cylinder.

      Several tries (~ 5 or 6) before each person could find even major cracks (~ entire thread length cracks)

      Generally it was required that a severely cracked cylinder be inspected and the crack pointed out to the operator-in-training before unknown cylinders could be inspected and all major cracks found.

A set of three cracked and three uncracked cylinders were inspected and repeated inspections were conducted on each cylinder. The major cracks (one or two per cylinder) were reliably found only after several trials by the inspector and being pointed out by a previously trained inspector. After this demonstration, the inspector could generally find all the major cracks on a repeatable basis. The size (length) of the crack could be determined approximately from the number of threads cut by the surface crack. No assessment of the reliability of this length measurement could be made. No estimate of the crack depth is possible with this method. The seams/folds in the neck near the lowest thread often are mistaken for small cracks (i.e. represent false readings), even when inspection is done by an experienced inspector.

e. Assessment of this method:

No quantitative estimate can be made of the ability of this method to find all cracks of a size beyond a specified size (i.e. the probability of missing cracks). The method is strongly dependent on the skill and diligence of the inspector. An independent check of the inspector's performance is possible, for example, through the use of standard test specimens. False readings are frequent in the lowest threads in the neck due to forming seams and folds. This method is useful as a rapid, inexpensive procedure for removing from service cylinders with significant, major surface cracks (~ 5 or more threads in length) but with a substantial probability of missing even these cracks if the inspector is not experienced or extremely diligent.

3. Fiber Optics Borescope

a. Inspection Equipment

A fiber optics instrument consisting of a bundle of optical fibers for imaging surrounded (concentricity) by a bundle of optical fibers for illumination was used to inspect the cracked and uncracked cylinders after cleaning and preparation as described above. This apparatus (American Optical Fiberscope Model FS100) could be used with a direct (straight-on) or right angle viewing attachment to inspect the threads in the cylinder neck. This apparatus had a working distance of 1/2 to 2 inches and the eyepiece provided a magnification up to 10x. The illumination was provided by a high intensity halogen light source.

b. Results:

Three cracked and three uncracked cylinders were inspected by three different people on numerous trials after substantial familiarization and practice with the apparatus. The cracks in the cylinders could not be consistently and repeatedly found even when the inspectors knew of the presence of the cracks prior to the inspection. Inspections of unknown cylinders (where the operator did not know whether the cylinder contained cracks or not) were generally unsuccessful in that major cracks were frequently missed.

c. Assessment of the method:

This particular fiber optics borescope did not provide as reliable or consistent results as the simple optical examination with the magnifying "dentist" mirror. This procedure did not demonstrate sufficient reliability to be considered to be an acceptable inspection method. Improved fiber optic inspection devices are available that incorporate magnifying lens. These devices may be expected to improve the reliability of the visual inspection procedure. However, the limited availibility of the more advanced fiber optics devices and the relatively high cost of such devices (approaching the cost of the electronic inspection apparatus described below) makes such devices limited in their applicability for inspecting cylinders.

Liquid Penetrant Inspection

1. Background:

All cracks identified to date in failed or inspected cylinders have been found to be exposed to the inner surface of the threads in the cylinder neck. Because all cracks are open to the surface, it was expected that the use of a liquid penetrant would substantially enhance the ease of identifying cracks in the cylinder.

2. Inspection Procedure:

The cylinders were thoroughly cleaned in a degreasing solution in an ultrasonic cleaning bath rinsed in water and dried prior to use of the liquid penetrant. A visible dye type of penetrant (Spot chek manufactured by Magnaflux Corporation) was used for the inspection. The procedure recommended by the manufacturer consisting of cleaning, application of the penetrant, removal of the penetrant, and application of the developer was carefully followed. Observation following the application of the dye penetration was done by naked eye as well as by using the magnifying "dentist" mirror described above.

3. Test Results:

Numerous applications of the dye penetrant using applications by spraying, swabbing, wiping on with a fine cloth, and brushing were tried. In all cases it was not possible to adequately remove the excess penetrant from the root of the threads so that excessive "bleeding" could be avoided and the cracks could be readily found. In general, the entire threaded area turned pink (using a red dye penetrant and a white developer) so that the cracks did not stand out distinctly from the background. These attempts demonstrated that the threads made removal of the dye penetrant so unreliable and difficult that the use of liquid penetrants for this inspection is not likely to be successful. These tests were so unsuccessful that additional liquid penetrant testing, for example using water washable fluorescent penetrants, was not attempted.

4. Assessment of the Method:

The difficulty in easily removing the excess liquid penetrants from the internal threads in the cylinder makes the use of this method unreliable and not feasible for the specific application considered here. In addition, the cylinders would require thorough cleaning after using the penetrant test before they could be refilled with breathable quality air. This cleaning would add substantially to the time and cost required to use this inspection method.

Radiographic Examination

1. Background:

The relatively thin wall of the aluminum in the unwrapped portion of the cylinder neck and the expected orientation of the cracks indicated that relatively deep cracks (>20% of the wall thickness) should be readily detected by conventional radiography without the need for further development of the radiographic procedures. Radiography also offers the advantage of not requiring any special cleaning or preparation of the cylinders prior to inspection and does not result in any contamination of the cylinder that requires special cleaning prior to refilling with air for breathing.

2. Inspection Procedure:

The radiography was conducted at NBS using a constant potential x-ray source set at an energy of 150 kv, with a source to film distance of 2 meters to improve the radiographic image definition. An exposure time of 2 to 3 minutes was required when using fine grained film processed by normal, manual film processing procedures. The cylinders to be inspected were placed vertically, upside down (sitting on the neck of the cylinder) on the unexposed film and the radiographic source was placed above the bottom of the cylinder and the radiation passed through the bottom of the cylinder as well as through the shoulder and neck of the cylinder before reaching and exposing the film. Any cracks in the neck of the cylinder showed up as a radial indication on the film.

3. Test Results:

Six cylinders were inspected using the procedure described above. Three of these cylinders, that were known to have cracks, showed distinct cracks extending perpendicularly from the hole in the neck of the cylinder. Single cracks were found in cylinders No. 43690 and 44030 and two cracks (180° opposite) were found in cylinder No. 43743. Three cylinders that were found not to have cracks when visually inspected and from cylinder lots not expected to exhibit cracking were inspected. Two of these cylinders did not show cracks when examined by radiography. However, a third cylinder (No. 46248) did show a single crack in the neck in the cylinder.

The forming seams and folds near the neck of the cylinders were visible on the radiograph. However, using the procedure described here of having the x-rays pass vertically through the bottom of the cylinder, these seams or folds can easily be distinguished from true cracks. The true cracks extend for a considerable depth into the wall of the cylinders, whereas, the forming seams or laps extend only a very small distance (significantly less than the depth of the threads) into the cylinder wall. Not only can the cracks be distinguished from the seams or folds by this radiographic procedure but the depth (in the through-wall direction) can be determined from the radiographs.

Sections taken from the neck of cracked cylinders were radiographed in several orientations and at a closer distance to the film. These tests showed that the cracks were actually a closely spaced series of parallel or branched cracks and that the width of the cracked area could be as much as approximately 1/16-inch.

4. Assessment of the Method:

The radiographic method used for this inspection proved to be feasible and reliable for finding and measuring the depth of cracks in the threaded area of the neck of these cylinders and did not give significant false indications. The reliability of this procedure is considered to be acceptable when normal radiographic procedures are used and does not require additional development or modification. This procedure can be used to determine the depth (through the wall dimension) of the crack, but no estimate of the length of the crack can be made from the radiographs alone. This procedure has the further advantage that the cylinder does not suffer any contamination requiring additional cleaning prior to refilling with breathable quality air. The only limitation of this procedure is that it requires specialized radiographic equipment and highly trained and qualified personnel. The procedure would generally be done by bringing the cylinders to the radiographic laboratory. However, portable equipment and procedures are readily available to permit this type of inspection to be done anywhere in the field.

Further attempts at radiography of cylinders were made by Luxter USA, Inc. and by NASA. In these tests, multiple exposures were made of the neck area of the cylinders from various angles to locate the crack regions. The results of these tests indicate that the cracks can be found but that a significant number of false indications are caused by the seams and folds in the neck of the cylinder. These false indications can not readily be distinguished from the true cracks and therefore, a significant number of uncracked cylinders would be unnecessarily rejected when this procedure is used.

Ultrasonic Inspection

1. Background:

The presence of known sharp cracks oriented perpendicular to the surface of the neck of the cylinder suggests that ultrasonic inspection methods should be feasible to detect and possibly determine the size of the cracks. The commercial availability of relatively inexpensive and portable ultrasonic test equipment for doing either longitudinal or shear wave type ultrasonic inspection made these techniques appear to offer substantial promise for inspecting the cracked cylinders.

2. a. Contact Tests

A direct contact transducer, approximately 1/8 inch in diameter, which transmitted a longitudinal wave perpendicular to the outer surface of the cylinder was used in a frequency range of 5 to 15 MHz. No attempt was made to custom fit a transducer to the contour of the cylinder neck.

b. Immersion Tests - Longitudinal Waves

Cylinders were immersed in a water bath to ensure positive coupling of the ultrasonic signal to the cylinder and optimum transmission of the ultrasonic waves into the cracked neck of the cylinder. Longitudinal waves with frequencies of 10 to 15 MHz were passed from the outside of the cylinder wall through the cylinder wall to detect cracks. Two cylinders known to have cracks in the neck were examined.

c. Immersion Tests With Shear Waves

Cylinders were immersed in the water bath and longitudinal waves were angled to the cylinder to convert the longitudinal waves to 45° shear waves in the cylinder wall. Test frequencies of 10 to 15 MHz were used. Two cylinders known to have cracks in the neck were inspected by this procedure.

3. Test Results

Two cylinders with known cracks in the cylinder necks were examined using the three procedures described above. None of the three procedures could distinguish between cracks and the threads when the cracks were near the threads. Using all three procedures, known cracks that were several threads long and which extend through a significant portion of the wall thickness could not be detected with any reasonable degree of confidence or reproducibility. The only crack that could be found with any reliability was a large crack that extended entirely through the wall (the cylinder was a "Leaker"). This crack could be located only with the direct contact transducer procedure.

It was concluded that the very large and highly variable grain size in the neck of the cylinder seriously interfered with the ultrasonic signals and resulted in many false signals as well as uncertainty in detecting the presence of cracks in the cylinder. In addition, the geometric reflections due to the threads interfered with the ultrasonic signals and made the detection of known cracks difficult.

4. Assessment of the Method:

None of the three ultrasonic procedures tried, proved to be suitable for detecting even known large cracks in the necks of the cylinders in the vicinity of the threads. All procedures tried also produced an unacceptable number of false readings in areas of the cylinder neck where cracks were known to be nonexistent. From the lack of success with these initial ultrasonic tests, it was concluded that additional ultrasonic test method development was not warranted.

Eddy Current Test Methods

1. Background:

Eddy current methods are well developed for use in detecting surface or near surface cracks in conducting materials and are especially well suited to locating cracks exposed to the surface in non-magnetic materials. Therefore, the eddy current method seemed to have a high potential for detecting cracks in the threaded neck of the composite-aluminum cylinders. In addition, the eddy current methods have the following advantages for the specific problem being studied here. 1) No contamination of the cylinder results from the examination method, 2) the test equipment is widely available commercially and is relatively inexpensive and 3) the test method is readily adapted to field use by inspectors without extensive training or experience. The three specific eddy current testing procedures described below were evaluated for detecting cracks in the cylinders.

2. Inspection Procedures

a. Single frequency test procedure without lift-off compensation. (High frequency amplitude sensitive).

The initial tests were conducted using a single frequency 3 MHz (amplitude sensitive) eddy current test instrument (the HALEC MK II, manufactured by Hocking Electronics, Inc.). This test instrument was chosen because of its simplicity, low cost, and ease of signal read out (by meter or audio signal). Specially made eddy current probes were required to permit examination of the threaded area of the cylinder. The first probe made consisted of a threaded lucite plug containing an eddy current coil that could be screwed into the threaded cylinder. A modification was made to the probe in a second probe design which consisted of a split plug to produce a spring loading effect and thereby more accurately control the "stand-off" distance (lift-off) between the probe and the threaded wall of the cylinder.

b. Impedance-Plane Variable Frequency Test Procedure

A test instrument that permitted the test frequency to be varied and that permitted the signals from the bridge circuit to be displayed in such a way that the phase and amplitude are displayed separately was tried using only the split "spring" probe described above. This procedure makes it possible to balance the instrument to distinguish between "defects" indications that are displayed on the vertical axis of the oscilloscope and the lift-off signals that can be displayed on the horizontal axis of the oscilloscope. The lift-off signals are all of a similar phase, whereas, the defect signals are of a different phase. Therefore, signals that represent defects can be separated from signals that represent changes in lift-off. By separating the amplitude associated with each phase, it is possible to reliably identify only signals associated with defects and therefore eliminate "false indications" caused by changes in lift-off distance.

These tests were first run with the split spring probe described above using a 1 MHz operating frequency even though the probe was designed to operate at a 3 MHz frequency. A third probe was designed with an impendence such that it operated at 500 KHz for maximum sensitivity and the tests described above were repeated.

3. Test Results:

a. High Frequency Amplitude Sensitive Test Instrument

Six full cylinders and heads cut from six cylinders were examined using this procedure using both the rigid and spring loaded high frequency probes at a single operating frequency of 3 MHz. In all cases, a strong indication (change in amplitude) was obtained at the point in the cylinders or cylinder heads where cracks were known to exist. However, due to changes in lift-off distance, numerous "false readings" as indicated by a change in amplitude occurred in positions where no cracks where found. These results are unacceptable because these false readings will cause the unncessary rejection of cylinders which do not contain cracks.

b. Impedance-Plane, Variable Frequency Test Procedure.

These tests permitted the amplitude change due to a defect to be separated from the amplitude change due to a change in lift-off distance by associating the amplitude change with the change in phase. This procedure was used with both the 3 MHZ probe (at an operating frequency of 1 MHz) and the 500 KHz probe (operated at 500 KHz) to examine six full cylinders and six cut cylinder heads. Both heads and cylinders known to contain cracks as well as ones known to be free of cracks were examined. Cracks were reliably and reproducibly found in all tests and false signals due to changes in lift-off distance could be clearly distinguished from signals from defects. The 500 KHz probe worked significantly better than the 3 MHz probe in that stronger and more reproducible signals were produced from cracks and the signal due to changes in lift-off distance were more clearly distinguished from the crack signals.

4. Assessment of the Eddy Current Method:

The eddy current test method has been demonstrated to be feasible for finding cracks with a high degree of reliability when specially designed probes are fabricated for this application and the signals are processed through an electronic circuit that separates changes in amplitude and phase. It is necessary that changes in signal amplitude be separated into changes due to the presence of a crack and changes due to variation in lift-off spacing. Using spring loaded probes designed to fit into the cylinder threads, the inspection procedure is rapid and simple and no special cleaning of the cylinder is required before or after the inspection. The operation of the test apparatus and the signal interpretation from the eddy current probe are relatively simple and should require only modest training of the inspector to achieve acceptable results. False readings should be easily kept to a low and acceptable level. The test apparatus required is readily portable, moderately expensive (less than $10,000), and the test procedure can be satisfactorily used in a production or retest facility environment.

With this inspection procedure, cracks in the cylinder threads can be readily and reliably located but can not be precisely sized. An approximate length of the crack can be determined from the number of threads which the crack cuts. The depth of the crack can not be determined with this method with any measureable degree of precision. The minimum depth of crack that can be detected with this method was not determined experimentally but is believed to be less than the distance between the root and crown of the threads.

A simpler eddy current procedure in which only changes in signal amplitude and not changes in signal phase are measured was attempted and found to be not feasible for measuring cracks in the cylinder threads. Although all known cracks were readily found with this procedure, an unacceptable number of false indications occurred due to changes in lift-off distance causing a change in signal amplitude which was indistinguishable from changes in amplitude due to the presence of a crack. Use of this procedure would result in an excessive number of cylinders being rejected during inspection when they did not contain cracks.

Summary

Of the methods considered those that appear to have the greatest potential are eddy currents, radiography and visual/optical testing. In the tests made at NBS the eddy current approach was shown to be capable of detecting known cracks consistently and giving some size (length) information by counting the number of threads over which a signal was obtained. The phase and amplitude sensitive, scope-type instrument gave good defect signals and discriminated against lift-off effects. Field use of the eddy current method presents little problem.

Radiography through the bottom of the cylinder was shown to be useful for detection of cracks having some depth and for discriminating against false signals due to folds and seams. The radiographic technique can be performed in the field but would require trained operators familiar with radiation equipment and procedures.

The visual/optical method is relatively simple to use in the field. It certainly offers the potential for detecting large cracks. The method is obviously highly dependent on the operator.

A summary of the NDE methods tried and considered is given in Table I.

CONCLUSIONS:

Several non-destructive evaluation methods were tried and evaluated for use in finding cracks in the necks of composite, aluminum, hoop-wrapped cylinders. The following assessment of these methods was made:

1. Eddy Current Procedures - this method was shown to be feasible and reliable when low frequency probes (~500 KHz) were used and the signal was processed to separate changes in signal amplitude from the presence of cracks and from changes in lift-off distance. These procedures were judged to be the most reliable of all NDE methods evaluated and adaptable to inspection in the field by inspectors with a minimum level of expertise.

2. Radiography - this method was shown to be reliable when the source was positioned to shoot throught the bottom of the cylinder in a single exposure. The depth of the crack can be estimated with this procedure. This procedure can be conducted with portable equipment in the field under most conditions but would require a well qualified operator and an authorized inspection procedure.

3. Visual Inspection - this method was demonstrated to be feasible for finding major cracks in the cylinder necks when proper lighting and optical magnification mirrors were used to assist the visual inspection. No assessment of the accuracy of this method could be made and the results are strongly dependent on the skill and diligence of the inspector. This method is simple and readily adapted to use in field sites.

4. Dye Penetrant - the use of dye penetrant procedures to enhance the visual inspection was shown to be not feasible due to the difficulty in adequately removing the dye penetrant from the threads in the cylinder.

5. Ultrasonic Procedure - these procedures were shown to be not feasible due to many false readings and to the inability to find cracks known to be in the cylinders. The presence of threads and large grains was believed to be the cause of the lack of success with ultrasonics.

6. Acoustic Emission Procedures - these procedures were not attempted experimentally but were judged to be not feasible because of the location of the cracks, the presence of the glass wrapping on the cylinder, and the lack of clear acoustic signals from the intergranular cracks present on the cylinder.

RECOMMENDATION FOR FUTURE WORK

1. Fabricate an optimum design for a spring-loaded, low frequency (~500 KHz eddy current probe.

2. Develop and document a specific test method and operator qualifications for performing the eddy current inspection.

3. Develop and document a specific test method and operator qualifications for performing visual/optical inspection.

4. Perform an inspection on a sufficiently large sample of cylinders (~500) by both the optimal eddy current and visual inspection procedures to accurately access the reliability of these two methods.

5. Establish requirements and procedures for inspection of all cylinders currently in use. Requirements should be established for immediate inspection, inspection during periodic retest, and at the time of any modification (i.e. retrofit of neck rings).

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Table I

Comparison of NDE Methods

Method	Description	Results	Advantages	Disadvantages	Suggested Future Work
Optical/visual	1 x mirror 2 x mirror fiberoptics-borescope	1. finds large cracks 2. not reliable for small cracks (~2-3 threads long) 3. misidentifies seams/folds as cracks	1. low cost 2. ease of use 3. readily available 4. minimal equipment & operator training 5. easy to do in field	1. significant probability of missing cracks 2. very operator sensitive 3. false readings due to seams/folds 4. not possible to quantitatively access reliability	high magnification and intensity illumination optics scope
Dye penetrant	spot check (2 part penetrant/developer	1. not feasible-dye bleeds into threads and cannot be removed	1. low cost 2. should significantly enhance visibility of cracks	1. difficult to use on internal threads 2. messy to use-requires substantial cleanup to avoid contamination of air	1. try water washable fluorescent
Radiography	1. 150 KV-shot through bottom of cylinder	1. feasible 2. reliable 3. highly sensitive	1. fast 2. good sensitivity 3. no clean-up required	1. expensive equipment 2. highly skilled operator 3. expensive	1. try smaller focal spot source inside cylinder
	2. multiple shots	1. not feasible-too many false readings	1. no clean-up required		
Ultrasonics	1. longitudinal beam surface probe	1. could not find large cracks 2. many false readings	1. uses commercially available equipment 2. no clean-up required	1. false readings due to seams/folds and threads	none
	2. immersion tests (shearwave and longitudinal waves)	same	1. reliable coupling 2. uses commercial equipment	1. lack of sensitivity 2. many false readings 3. high level of operator skill required 4. large grains and threads limit observation of signals from defect	1. development and optimizat of probes 2. try electromagnetic-acous transducers (EMAT)

Table I (con't)

Method	Description	Results	Advantages	Disadvantages	Suggested Future Work
Eddy Current	1. simple-impedence amplitude instrument	not feasible-false readings	1. clean 2. can be done in field 3. direct readout	1. special probes required	none
	2. lift-off compensated, impendance amplitude instrument	not feasible-false readings	1. clean 2. can be done in field 3. direct readout	1. special probes required	try lower frequency probes
	3. phase and amplitude instrument (oscilliscope type)	feasible, excellent sensitivity	1. clean 2. can differentiate cracks and lift-off	1. moderately expensive instruments required 2. operator skill moderately high 3. special probes required	optimize low frequency probes
Acoustic Emmision		not attempted-considered to be conceptually unlikely to work	1. clean 2. would be possible to do during routine filling	1. expensive equipment 2. high operator skill required 3. can not easily separate signals from glass windings, motion of valve, geometric reflection	try on vessels known to have cracks

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4. TITLE AND SUBTITLE

Assessment ~~Evaluation~~ of Nondestructive Evaluation Methods For Hoop-Wrapped Cylinders

5. AUTHOR(S)

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6. PERFORMING ORGANIZATION (*If joint or other than NBS, see instructions*)

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

Cracks have been found in the threads in the neck of hoop-wrapped composite cylinders used as part of air breathing apparatus. These cracks have led to leaking and rupture of the cylinders during normal service operation. Therefore, a reliable non-destructive evaluation method was required to be developed to identify and remove from service any cracked cylinders. Several standard nondestructive evaluation methods were used and evaluated for the inspection of these cylinders. The eddy current techniques were found to be the most reliable and practical for this application. Radiography was found to be reliable but judged to be too complex and expensive for wide scale use in the field. Ultrasonic and acoustic emission techniques were found to be unsuitable.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

composite cylinders; crack detection; eddy current; Non-destructive Evaluation; pressure vessels; ultrasonics

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