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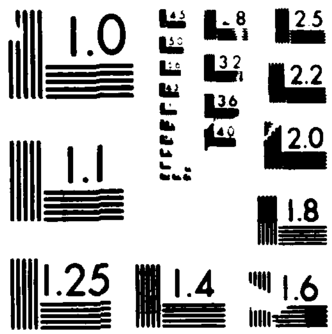

MICROCOPY RESOLUTION TEST CHART

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TECHNICAL REPORT ARPAD-TR-87006

REFERENCE STANDARDS FOR NONDESTRUCTIVE TESTS

HENRY HARTMANN

OCTOBER 1987

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& CHEMICAL COMMAND
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Reference standards are the prime element of nondestructive tests. Standards contain the flaw or a simulated representation that is being sought, such as cracks, and these flaws are in a geometry that simulates the parts to be tested. This report emphasizes cracks in metal parts, how to calculate crack sizes, and how to simulate cracks in reference standards.

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NONDESTRUCTIVE TESTS

Proof Tests

Proof testing is the oldest form of nondestructive testing; all of the acceptable parts are perserved. Chain and rope are subject to proof test loads to verify that they are safe for use at lower "rated" loads. A reference standard normally is not used in these simple pull tests. What is used is a master load cell gauge red-lined at the desired strength. This value of strength has been determined by prior destructive tests of sound as well as purposely weakended rope and chain. The literature accompanying rope and chain will often designate the rated load and, for better quality material, may reveal the proof test load.

Proof test loads have minimum values, applying at least the minimum designated value. The accuracy of the load cell gauge used to measure minimum proof test pull should be at least 0.1% of the proof strength value. Therefore, a 1,000 kilogram proof test load would require a load cell graduated in increments of kilograms and accurate to within one kilogram at and around the 1,000 kilogram value. Unless constructed for continuous use, such a gauge would be used only to check the accuracy of the pulling mechanism.

There was a time when barrels for cannon had to be cast. Pistols and rifles, being much smaller, were made from wrought iron. However, the larger cannon barrels were too big to be hammered or rolled into shape; therefore, they were cast. To check for soundness of the cast metal, all guns were (and are still) proof tested. Extra propellant (a proof charge) is used to assure that all gun barrels have the extra strength needed for safe use.

Data on proof test pressures can be gathered in laboratories by special guages incorporated into modified gun tubes. Pressure transducers provide a pressure-versus-time trace. Copper crush gauges, using copper balls sandwiched between hardened pistons and anvils, provide peak pressure measurement by the size of the flats squeezed into the copper balls.

Expanding Mandrel

For cylindrically-shaped parts containing at least one open end, a mechanically expanding mandrel is a relatively cheap and rapid method for proof testing the hoop strength of each part. Expanding mandrels are generally designed with a conical wedge over which tapered segments are held in place. As the conical wedge advances, the tapered segments expand outward radially.

For use in manufacturing, the conical wedge of an expanding mandrel will generally have a fixed stroke (i.e., the mechanism driving the conical wedge will bottom against a fixed stop). A fixed stroke is not acceptable for nondestructive tests. For NDT purposes where the hoop strength of a part is being evaluated, a fixed peak force drives the conical wedge until the resistance to expansion stops all movement. Normally, this test will leave a slight permanent deformation in the part. Parts of inadequate strength will permit excessive expansion. The conical wedge will pass the normal limit of movement and trigger a reject alarm. The rejected part will have greater permanent deformation, perferably being of unusable size. Sometimes the parts will fail with a snapping sound while at other times a failure will be quiet.

The repeatability of the constant peak force that moves the expanding mandrel is important. Usually, compressed air drives a piston in a pneumatic cylinder. Line pressure in compressed air lines can vary substantially. Therefore, a precision air regulator feeding an oversized air cylinder will be needed for a constant-air-pressure, constant-force design. An oversized air cylinder will be needed as the working air pressure must be somewhat less than the minimum line pressure that could occur. Hydraulics can also be used as a prime mover.

Variations in the applied stress from an expanding mandrel can be measured by use of a strain gauged "good" part.

Good and reject reference standards consisting of sound and weakened parts can demonstrate the effectiveness of an expanding mandrel test.

Hydrostatic

Hydrostatic proof testing presents more of a safety hazard to operators than expanding mandrel tests. Weak parts often burst into pieces with a loud bang, and operators must be protected from flying fragments. For example: 155-mm M549 artillery warhead bodies were 100% hydrotested. The reason for the hydrotest was that the warhead bodies were made from a somewhat brittle HF-1 high fragmentation alloy steel. The hydrotest consisted of applying an internal pressure of 15,000 psi minimum, holding the pressure for 15 seconds, and then releasing the pressure. Of the many warhead body failures that occurred, most occurred during the buildup in pressure. The rejects would burst amidst a great racket of rattling fragments and flying spray. A few warheads burst during the peak pressure holding period, and a few had failed hydrotest by leaking so badly that peak pressure could not be attained.

INTRODUCTION

This technical report is written for people familiar with nondestructive tests. Definitions of key technical words and phrases are listed in the glossary. The definitions of key technical words and phrases are listed in the glossary. The definitions are specific to the particular use of the words or phrases in this report. Use of the glossary can aid in a better understanding of this report.

Short cuts need not be desireable. Following is a typical response from a contractor when asked, "Where are the reference standards?" "What do I need a reference standard for? My nondestructive test (NDT) equipment is working just fine. Every once in a while it even rejects a part. So what do I need a reference standard for?"

There are a few simple NDTs such as some strength or proof tests, where reference standards are not needed. For most NDTs, the use of reference standards are essential for accurately setting-up NDT equipment to achieve adequate sensitivity. If referencing cracks, a proper standard containing a simulated or real crack of known size will permit proper adjustment of the NDT equipment so that cracks of a designated size or larger will be rejected. Reference standards provide a direct correlation between NDT equipment and the size of sought defects.

Reliable sensitivity is the most important factor in the successful use of nondestructive testing. If the NDT method has the ability to detect the presence of small defects that can unacceptably weaken the part being tested, and the NDT can repeatably detect similar small defects over and over again, then the method is judged to have adequate reliability of sensitivity for the application.

Reference standards also permit control of accuracy on the measurement of the size of sought defects. Should something alter the established sensitivity of detection, use of a reference standard will permit evaluation of any change in detection sensitivity and will permit proper adjustment.

Emphasis in this report is on cracks. There are many other types of discontinuties that can weaken or make parts unacceptable; however, cracks in high strength metal parts have been found to be a serious menance.

The examples used in this report often cite U.S. Army munitions. The U.S. Army has invested heavily in NDT to assure that its ammunition is safe. Nondestructive testing has been a major influence in the increased performance of the U.S. Army's artillery weapon systems while maintaining the same levels of safety.

All NDT reference standards that look similar to the item being tested are colored bright red for easy visual recognition. Losing a reference standard among produced items is a dangerous situation.

PHILOSOPHY

The basic purpose of NDT is to assure that all defects are rejected. That is, all defects which could cause unsatisfactory performance or, more importantly, all defects which are unsafe and which could cause bodily injury or even death shall be segregated from the acceptable parts. To assure that 100% segregation of all unsafe and unreliable causing defects is achieved, a portion of the rejects that are safe and reliable shall be scarificed.

NDT reference standards normally contain man-made flaws that simulate the minimum size of defect that is to be rejected. In the case of cracks, the size of the flaw is first determined by calculating the minimum size of critical cracks. Then a safety factor is applied, based upon various parameters of the NDT to be used, to assure that all critical sized cracks plus relatively large safe cracks are rejected. The safety factor reduces the critical crack size to the smallest size of crack that would be rejected. This crack size is the rejection criterion. Similar analyses are used for making reference standards for other types of nondestructive testing and other types of defects.

Very few NDT acceptance reference standards are used. When they are used, they check the error of the NDT equipment. For example: In an accumulation leakage test, an inert "no leakage" reference standard can be used to determine what portion of the permissable leakage tolerance is being used by internal leakage of the test equipment. In nondestructive tests for cracks, acceptance reference standards are not used because it would prevent contractors from designating how small an acceptable flaw they would prefer to discard. Some contractors prefer to play it close while others perfer an added safety factor to assure all defects will be rejected.

For nondestructive testing, rejection reference standards are perferred. There are many different designs of rejection reference standards that can be created. The goal is to make a stable simulation of minimum sized rejectable defects incorporated into hardware that simulates the parts to be tested. Even with different models of NDT instruments, the rejection reference standard accurately represents what is unacceptable without excessively penalizing any manufacturer.

The concept of an NDT reference standard should be such that all involved witnesses accept its validity.

During this hydrotest, the operator was busy loading and unloading test stations. Little time was left for analysis. Automatic controls (red light or green light) revealed whether or not the projectile body had successfully passed hydrotest. When a red light was encountered, the peak holding pressure of 15,000 psi had not been reached. Either the warhead body had a leak or the "O" ring hydraulic fluid seal against the nose of the warhead body was leaking. The protective steel shroud that retained flying fragments masked visual observation of where the leakage was coming from.

The red light-operator interface, turned out to be a crucial weakness for this hydrotest. A warhead body with a huge crack through the wall that ran three-quarters of the way around the body was accepted by an operator and wound up in a loading plant. Fortunately, an alert loading plant operator saw the crack and rejected the warhead body. The problem was human error. A busy operator forgot the warhead body came out of a red-lighted station and failed to reject the cracked warhead body. The solution to this problem should have been to remove the decision-making action of acceptance versus rejection from the operator.

Even though no reference standards were used in this hydrotest, two could have been used. A no-leakage reference standard could have quickly determined the adequacy of suspect "O" ring seals. A gross-leakage reference standard could have assured that all stations were rejecting cracked warhead bodies that leak.

Liquid Penetrant Tests

No matter how deep the defect, all that liquid penetrant can reveal is whether or not a defect occurs in a surface. Unless the indication is large, there are few clues as to the depth of a defect. As a result, rejection is based solely upon the revealed surface image of a defect.

Plugs

Circular cracks can be simulated by press-fitting plugs into the metal to be tested. Plugs can be easily fitted into sheet metal as thin as 1 1/2 mm (0.06 in.). Metal from the same sheet should be used for the plug. Plugging can be accomplished by reaming a fine finished hole, turning a slightly oversized plug from a small piece of the same metal, aligning plug over hole, and pressing together. Care must be taken to make adjacent sides absolutely flush with one another. Usually, a final polish or grind will be needed for an absolute flush fit all around on both sides.

Plugs can be inserted into all kinds of part geometry. When properly done, the plugs are not obvious. They should be located where defects tend to cause great weakness and where defects are not easy to see.

Size of the plugs should be small. For example: if the reject criterion is any crack greater than 2 mm (0.08 in.) in length, then the plugs should be 2 mm in diameter.

The advantage of a plug simulating a crack is that the simulation is in all directions on a surface. Any directional bias in the revelation of cracks (possibly caused by rinsing) will be revealed by a 360-degree crack.

Quench Cracks

Natural cracks can be created by quenching. Localized heating just short of melting and then rapid quenching in frigid water can induce quench cracks in higher strength, lower ductility metals. The cracks tend to occur around the hot spot.

With just a few cracks in known locations, it would be easy to observe a loss in the sensitivity of revelation of a liquid penetrant. Special quench processes to achieve desired distributions of cracks are feasible.

Plugs also provide the versatility of incorporating natural cracks of known size into a reference standard. The natural cracks could be made to the depth and length required and then transferred, within a plug, to a reference standard. The orientation of a crack within a plug would be under complete control.

Quench cracked blocks and rings are commercially available in limited types and sizes of metals. Unless the metal to be tested is commercially available in the form of crack standards, it would be better to make your own quench crack reference standards.

Magnetic particle testing quench crack rings, if of the same metal, can be used as liquid penetrant reference standards.

After usage to reveal the sensitivity of a liquid penetrant, the reference standards must be cleaned of the adhering liquid penetrant. Cleaning is best accomplished by first wiping off excess penetrant with an absorbent material, then soaking the standard in an ultrasonically agitated solvent for half an hour or so, and finally vapor degreasing. If an ultrasonic vapor degreaser is used, the last two steps consist of hanging the reference standard in the bottom pool of solvent and then later lifting the part above the pool.

Magnetic Particle Tests

A number of commercially available reference standards already exist for use in evaluating the sensitivity of magnetic particle tests.

Ketos Ring

The 5-inch diameter by 7/8-inch thick steel ring is used to evaluate the effective depth of magnetic particle tests. Small round holes running parallel to the polar axis of the ring and passing through the ring from face to face exist at increasing depths below the outside diameter surface. After circular magnetization of the ring and application of magnetic particles, the number of holes revealed by magnetic particles on the outside diameter of the Ketos ring determines the effective depth of the test (ref 1).

Quench Crack Rings

Steel rings resembling the general shape and size of a Ketos ring are commercially available with fine quench cracks on both faces. Visibility of these fine quench cracks by means of a magnetic particle test indicates the sensitivity of the applied magnetic particle test. Unfortunately, the quench cracks are randomly scattered and are not arranged according to depth and tightness. Generally, the shallower the crack, the tighter it is. If quench cracks could be arranged on a plate according to depth (i.e., the deepest crack being on one end and the shallowest crack on the opposite end) and if the depths were known, then magnetic particle testing as well as liquid penetrant testing could have their sensitivities quantified by that portion of the reference standard plate revealing cracks.

Plugs

Large plugs have provided the best reference standards to date for magnetic particle testing of artillery projectile bodies. Reference standards containing large plugs have been made for and used in the production of 152-mm and 155-mm artillery projectile bodies. During production testing, only circular magnetization was used. The circular magnetization came from a centrally positioned copper conductor bar running down the length of each projectile body.

CAUTION Use of this technique on high carbon steels can create a thin layer of white martensite. Poor electrical conductance where the copper conducting rod contacts the base of the projectile body can cause localized heating. Rapid quenching of this hot spot can caused white martensite, an extremely brittle form of steel.

All transverse oriented cracks in artillery projectile bodies were better revealed by circular magentization than by longitudinal magnetization (using a big coil). The circular magnetic field was [illegible] more intense than the logitudinal magnetic field. As a result use of the longitudinal magnetic field has been eliminated.

Large plugs made from the thick bases of projectile bodies were finely finished, frozen, and press fitted into bored holes in the side walls of the projectile body reference standards. Plugs were placed front and rear and were machined smooth with the mating walls on both the inside and outside. A slightly different grain texture revealed the pressence of the plugs. Magnetization just after coating with a solution of magnetic particles reveals the circular joints all the way around the plugs. However, the longitudinally oriented segments of the circular joints, being at right angles to the circular magnetic field, show up much better than the transverse oriented joints (fig. 1).

After prolonged use, the magnetic particle solution will pick up adulterants, and the indications of the plug joints that run parallel to the magnetic field will become finer and finer. Finally, the revelation of a circle will break (fig. 2). The break is the signal from the reference standard that the sensitivity of the magnetic particle test is unreliable. To regain magnetic particles test sensitivity, empty, clean, and recharge the tank; clean the ultraviolet lamp and filters; etc.

Plugs can be used with any direction of magnetic field. The criterion is: if a full circle of magnetic particles is not seen, the magnetic particle test is unreliable.

Radiography Tests

Radiography is sensitive to the presence of voids, inclusions, porousity, and cavities. The sensitivity of radiography to cracks depends upon the gap within a crack and the angle of orientation along the wall of a crack with the direction of radiation. Wide crack gaps together with parallel orientation of crack and radiation are best. Cracks with wide separation gaps can be readily detected even at an angle of 45 degrees with the direction of radiation. Tight cracks, even when they are parallel to the direction of radiation, are difficult to detect.

Penetrameters are the standard devices used to demonstrate the sensitivity of each radiograph. Those used in America usually consist of a strip of the same general type of material (metal, plastic, rubber, etc.) as the object to be tested and are chosen to have a thickness of 2% of the material to be tested. The diameter of the holes in the penetrameter are equal to the penetrameter thickness (1T), twice the thickness (2T), and four times the thickness (4T). A penetrameter is placed on the radiation source side of the object being tested. If the outline of the penetrameter on the radiograph is clear and the 2T hole can be seen, then the penetrameter sensitivity of that radiograph has been demonstrated to be 2% (additional penetrameter information in ref. 2).

There are instances where sensitivities better than 2% are essential. This would call for thinner penetrameters.

Ultrasonic Tests

The technology of ultrasonics has been fine-tuned through the use of reference standards to automatically reject cracks that are slightly less than critical in size. Critical crack size is defined as the smallest crack size that could cause catastrophic failure (brittle fracture) under a given environment and load. Since ultrasonic testing can interrogate throughout the total volume of material, reference standards containing simulated cracks must be directly related to critical crack sizes. Knowing the values of fracture toughness, maximum tensile stress, and the yield strength, and assuming an elliptical shape of the crack with a length at least 10 times the depth (refs. 3 and 4), the minimum critical crack size can be calculated for whatever temperature produces the worst case. Once the critical crack sizes have been calculated for various locations on the parts to be tested, a factor of safety is applied to determine the minimum rejectable size of cracks. These minimum rejectable crack sizes are used as rejection criteria.

Since no one knows where and in what orientation critical cracks will occur, parts are ultrasonically tested in two directions perpendicular to one another. Otherwise, the test would be incomplete.

Slots

Slots can be made to physically resemble cracks. They can be made so narrow that, at first glance, they resemble short dark lines marked on the surface of a reference standard. For cylindrically shaped parts, such as steel artillery projectile bodies, slots are popularly used. It has been found that ultrasonic pulses, traveling through the walls of projectile bodies at an angle to the outer surface (as opposed to traveling straight in), provide stronger echo signals for detecting the presence of cracks. This is due to the "corner effect" where a double reflective bounce between the slot and the surface of the adjacent wall causes ultrasonic pulses to reverse their direction. The corner effect enlarges the effective area of the slot. Slower ultrasonic shear waves provide louder and clearer echo signals than the faster ultrasonic compression waves. The combination of scanning ultrasonic shear waves and slotted reference standards has provided a powerful nondestructive test for ridding all of the Army's high strength artillery projectile bodies of defective cracks.

There are many different ways to make narrow slots in metal (e.g., electric discharge machining, grinding, sand blasting, circular cutter milling, etc.). Control of the cross section of slots is very important, particularly when reflectivity is involved. The following slot-making processes are listed in order of maximum control (i.e., the precision, the ability to make identical slots over and over again):

Grinding--diamond wheel
--aluminum oxide wheel

Machining--tool steel slotting saws

Electric--discharge machining carbon electrodes

Sand blasting--fine aluminum oxide particles

Diamond grinding works well in hard metals. Slots ground with diamond wheels are extremely accurate and finely finished. One contractor used the following technique for measuring the features of each diamond wheel ground slot: ground one slot in a "before" block of the same metal, then ground the slot in the reference standard, and finally ground a third slot in an "after" block. The grinding was done in the same set up with a quick 1-2-3 action. The before and after blocks could be examined on optical comparators to accurately measure slot depth, width, and the connecting radii between the bottom surface and sidewalls. Surface finish measurements could be achieved by cutting the blocks open to provide access to the sidewalls. To make sure that the slot in the reference standard is the same depth, a very narrow blade point can be attached to the end of an indicator for direct measurement. Diamond wheels are costly and are made by fastening diamond grit to a metal wheel which makes them tough.

Bonded grinding wheels can also be used to grind slots. These narrow wheels are brittle and need many dressings in order to hold a sharp radii between the bottom surface and the sidewalls. This process is slow and touchy.

Machining slots, using very thin hardened steel slotting saws, works well in easily worked metals. Cutting softer metals permits the preservation of the sharp corners between the bottom surfaces and the sidewalls of the slots.

Electric discharge machining permits the cutting of square ended slots of uniform depth. Since the carbon ribbon electrodes are flimsy, tight shallow slots are usually cut in one plunge. The surface finish of the reflector sidewalls can vary.

It is essential to measure the features of electric discharge machined slots. This is best achieved by taking impressions in silicone rubber. A vacuum must be applied over the slot in order to remove all of the air from beneath the applied liquid silicone rubber. As a vacuum is pulled, air bubbles will come up through the liquid silicone rubber. No other way has yet been found to remove all of the air from narrow slots. After a slot impression is set, the removed impression can be cut into narrow slices with a razor blade for display on the screen of an optical comparator. Generally, thin slices from both ends and a thin slice from the center of the silicione rubber impression should reveal the dimensions and features of each slot.

Slots made by sand blasting are usually of such poor quality that they are unacceptable for use in ultrasonic reference standards. The major problem is the inability to hold the slot dimensions to tight tolerances.

The effective depth of a slot (for ultrasound) is the point where the bottom radius breaks away from the sidewall. The size of these radii should be kept below 0.1 mm (0.004 in.) for ultrasonic reference standards.

Surface finish of the sides of slots should not be a problem. Josef and Herbert Krautkramer (ref. 5) state: "The measure of the quantities rough and smooth is again the wavelength. If the differences in height of the surface irregularities are less than approximately 1/3 of the wave length, this surface can be regarded as smooth, as measurements by Kloth (ref 6) have shown." This can be checked easily by immersing a surface finish comparator in water. For example, and S-22 microfinish comparator made by GAR Precision Products, Inc., Stamford, CT and consisting of precision impressions of 2, 4, 8, 16, 32, 63, 125, 250, and 500 microinch surface finishes was used. Employing a 2.25 MHz focused transducer, the reflectivity of the various surface finishes was found to be constant. Switching to a 10 MHz focused transducer and repeating the scan, the reflectivity was found to be constant from 2 through 250 microinches. The reflectivity dropped a few decibels from the roughest 500-microinch surface finish.

Example: What surface finish should be specified for the sidewalls of slots used in ultrasonic reference standards for 155-mm M549 warhead bodies? The surface finish of quench cracks in HF-1 steel from rejected M549 warhead bodies was found to be 178 microinches. As a result, a surface finish of 250 microinches or better would be specified. The resultant reference standard could be used for ultrasonic frequencies from 1 to 10 MHz.

Example: How deep should slots be in ultrasonic reference standards for the 155-mm M549 warhead body? In the year 1970, critical crack depths were calculated for highly tensile loaded sections of the warhead. A safety factor of 4 was applied to the critical crack depths to obtain rejectable slot depths for ultrasonic reference standards. Over a decade later, it was found that these reference standards caused the rejection of natural cracks the smallest of which comes pretty close to critical crack sizes.

After measurement and acceptance of slots, the slots are filled with a noncorrosive room temperature vulcanizing silicone rubber to protect their reflective surfaces. Then, a thin coating of bright red paint can be applied all over the reference standard. A corrosion inhibitor in the ultrasonic water tank will protect any exposed steel. Excellent corrosion inhibition for steel can be obtained by including 0.05% by volume of sodium nitrite in water. Excellent corrosion inhibition for aluminum can be obtained by including 0.001% by volume of either sodium nitrite or sodium dioxide.

Round Holes

Round holes are usually easy to drill and can be used to simulate defects inside material. Either the side of a hole or its bottom can be used as a reflector. Round holes are used as reflectors in ASTM area/amplitude, distance amplitude, and distance/area blocks, IIW blocks and AWS resolution and shear wave sensitivity ultrasonic test blocks. For immersion applications, round holes can be sealed with plugs to maintain a constant reflective surface. Holes have been used in 105-mm and 155-mm artillery projectile bodies to simulate defects in ultrasonic tests.

Holes have three significant advantages over electric discharge machined slots for simulating cracks:

1. Provide a uniform 360 degree direction of reflectivity

2. Quickly applied

3. Low in cost.

Side Reflection

Reflecting from the side of a round hole produces two serious limitations:

1. Relatively small reflective area

2. Reflective area is dependent upon the size of the transducer and its distance

A contact ultrasonic test arrangement from which the reflective area on the side of a round hole can be calculated is shown in figure 3. The width of the active element in the transducer is "x". The active element is located distance "y" away from a round hole of diameter "d". All of these variables will be known. The two unknown variables are the reflective width "z" and the angle of incidence "β (beta)". Assume that all ultrasound pulses coming from the active element leave perpendicular to the active element (i.e., imagine that the active element has a microscopic piston-like movement in the vertical direction). From this piston movement, ultrasound is emitted vertically downward. It is known that the wave front of ultrasound spreads. However, consider only the vertical component of the ultrasound pulse to obtain a conservation value of the maximum reflective width z from the side of the round hole d. At a distance z/2 from the interconnecting centerline between transducer and hole, a vertical ray of ultrasound will strike the perimeter of the hole at an angle of incidence β. The ray will reflect from the hole at the same angle of incidence β, and in its travel will just contact the edge of the active element to signal the presence of an echo. Therefore, z/2 is the end of the reflective width for one side of the round hole.

There are two triangles of interest for finding the value of z. Both are right triangles. The first triangle is located within the hole where

$$\sin \beta = \frac{z/2}{d/2}$$

Simplifying, $\sin \beta = \frac{z}{d}$ (1)

Then there is the double β triangle located between the perimeter of the hole and the active element where

$$\tan 2\beta = \frac{x/2 - z/2}{y + \frac{d}{2}(1 - \cos\beta)}$$

Simplifying, $\tan 2\beta = \frac{x - z}{2y + d(1 - \cos\beta)}$ (2)

The proper way to solve equations (1) and (2) is to eliminate the variable β by substituting its value from equation (1) into equation (2). Unfortunately, this action makes the remaining equation more complex than the separate equations (1) and (2). As a result, the best way to solve for the width of the reflective side of a hole z is to assume a value of β and solve for the unknown variable z. When the value of z in both equations is numerically equal, then the value of z is known. This method is called iteration.

Example: Assume that a hole diameter d of 0.1 inch is located 1 inch away from a 0.5-inch diameter active element transducer. How much of the hole is a reflector to the transducer?

Assume values of β and solve both equations (1) and (2) until both values of z are equal. In the initial iterations, ignore the value of d(1 - cosβ) which is numerically small.

Table 1. Interations to determine the side reflections of a hole

d	x	y	β (deg)	z = d sin β	tan 2β	cos β	z = x - tan 2β [2y + d(1 - cosβ)]
0.1	0.5	1	10	0.0174	0.364		0.5 - 0.346(2) = -0.228
			2	0.00349	0.0699		0.5 - 0.0699(2) = 0.360
			4	0.00700	0.141		0.5 - 0.141(2) = 0.218
			7	0.0122	0.250		0.5 - 0.249(2) = 0.002
			6.9	0.0120	0.246		0.5 - 0.246(2) = 0.008
						0.993	0.5 - 0.246(2.0007) = 0.008
			6.8	0.0118	0.242		0.5 - 0.242(2) = 0.016
			6.85	0.0119	0.244		0.5 - 0.244(2) = 0.012

The answer to this problem is that only 0.012 inch of a 0.1-inch diameter hole acts as a reflector for a 0.5-inch diameter active element transducer located 1 inch away. Notice that the factor d(1 - cos β) is insignificant for this relationship (table 1, β = 6.9).

Some interesting relationships about side reflections from holes is shown in table 2 which was created from equations 1 and 2.

Table 2. Reflective width from the side of a round hole

Active element width x (mm)	Active element width x (in.)	Distance y (mm)	Distance y (in.)	Hole diameter d (mm)	Hole diameter d (in.)	Reflective width z (mm)	Reflective width z (in.)	Reflective portion z/d
12.7	1/2	50.8	2	12.7	1/2	7.1	0.028	0.056
				6.35	1/4	0.4	0.015	0.060
				3.18	1/8	0.2	0.008	0.064
6.35	1/4	50.8	2	12.7	1/2	0.4	0.015	0.030
				6.35	1/4	0.2	0.008	0.032
				3.18	1/8	0.1	0.004	0.032

The values of z reveal that as the size of the hole shrinks, so does its reflective width. However, the small portion of the hole that reflects (z/d) remains somewhat constant as the hole size shrinks.

If the size of the ultrasonic transducer is reduced to half, the reflective width of the hole as well as its reflective portion is also halved.

Even though the reflective surface spans only a small portion of the diameter of a hole, the reflective surface along the length of the hole equals the length of the active element within the transducer.

Example: What diameter of a flat bottomed hole will provide the same reflective area as its side reflection from a 2.54 mm (0.1 in.) diameter hole located 50.8 mm (2 in.) away from a 12.7 mm (1.2 in.) diameter active element? Assume there is a uniform distribution of energy across the pulse of ultrasound. The reflective width of a

2.54-mm diameter hole is 0.3 mm (0.012 in.) (table 1). The reflective area is 0.3 x 12.7 = 3.81 mm^2 (0.006 $in.^2$) along the length of the hole. A flat bottomed hole of the same reflective area would have a diameter of $(3.81/3.14)^{1/2}$ or 1.10 mm (0.043 inch) diameter. In this case, a flat bottomed hole reflector is equivalent to the side reflection from a round hole that is roughly double its diameter.

Bottom Reflection

Small flat bottomed holes provide a reflective area that is independent of the size and location of ultrasonic transducers. Furthermore, the reflectivity of flat bottomed holes can readily be reproduced. These are the two main reasons why the American Society for Testing and Materials (ASTM) board members have incorporated flat bottomed holes into their popular ultrasonic test blocks.

The ASTM has standardized designs for flat bottomed hole reflectors located inside cylindrical blocks. These blocks can be made out of any metal with 7075-T6 alloy aluminum and 4340 alloy steel being commercially available. The flat bottomed holes are available in different sizes (1/64-in. increments) and at different depths below the entry surface. Entrances to the holes are sealed to preserve the reflective surfaces.

The ASTM blocks can provide meaningful values of sensitivity that can be duplicated by others. For example: A quantitative designation for sensitivity is, "Set the gain for a full scale echo signal from a 3-0250 (3/64 diameter flat bottomed hole located 2.5 inches below the entrance surface) ASTM block." ASTM standards E127-11 and E428-11 (refs 7 and 8) provide detailed guidance on these ultrasonic reference standards.

Spherical bottomed holes have also been used at Picatinny Arsenal in ultrasonic reference standards. Ball-ended drills made from tungsten carbide are commercially available for drilling tough metal. The major advantage of spherical bottomed holes is their uniform reflectivity in many directions. Their major limitation is the minuteness of their detected reflective area.

Example: Calculate the portion of a flat bottomed round hole that would reflect if the hole were spherically bottomed? Since curved reflectors depend upon the size and distance of a transducer, no answer can be calculated without further information. Assume there is a 3.18-mm diameter hole located 50.8 mm away from a 12.7-mm diameter active element transducer. The reflective width from the side of the hole is 0.2-mm (table 2). The area of a circle is proportional to the square of its diameter. Therefore, the end portion of a 3.18-mm diameter flat bottomed hole that would reflect if it were a hemisphere under these conditions is $(0.2)^2/(3.18)^2 = 0.004$. A relative reflectivity of four tenths of one percent isn't much.

Paint Blisters

Paint blisters with pin hole openings in their tops make excellent ultrasonic reflectors when used in immersion testing. The paint blisters provide a strong return echo back down into the material when pulsed by 40-degree shear waves.

Eddy Current Tests Using Probe Coils Only

In metal objects, the less the value of electrical conductivity, the less the value of magnetic permeability, and the lower the applied eddy current frequency, the deeper eddy currents can penetrate. Use of eddy current tests on aluminum (high value of electrical conductivity) and steel (high value of magnetic permeability) result in shallow penetration.

Example: The depth of penetration of eddy currents of frequency 10 KHz in 7075-T6 alloy aluminum is 1.2 mm (0.048 in.) (ref 9). Raise the test frequency to 100 KHz and the penetration diminishes to 0.38 mm (0.015 in.).

In spite of the shallow eddy current penetration, the design of simulated cracks in eddy current reference standards can be directly equated to real cracks.

Slots

The only variable of importance for slots is size (i.e., the length, depth, shape, and gap of slots in eddy current reference standards are important). Variables such as surface finish of the sidewalls and radii between side and bottom surfaces are of no consequence. The same procedure used to calculate the size of ultrasonically rejectable crack sizes applies to eddy current rejectable crack sizes. The critical crack sizes are calculated and then a safety factor is applied to assure that natural cracks encountered at an angle of orientation are rejected if they exceed the minimum rejectable size.

Where the magnetic field is much larger than the minimum rejectable length of cracks, the slot should have the length and depth of a minimum rejectable crack size. The shape (sidewalls) of the slot can be elliptical or can have rounded ends or can even be of retangular cross section. The sidewall area should not be less than the area of an ellipse for the length and depth designated. A segment of a circle is unacceptable.

Where the magnetic field is half or less of the length of a rejectable crack length, the length of the slot can be the length of a rejectable crack or greater. If a slot length equals the length of a rejectable slot, then the shape should be retangular. Slots of much greater length can have rounded ends.

The width (gap) of the slots is important. Slot width affects the phase angle (the angle between electrical induction and electrical resistance) of detecting eddy currents. Slots should be made no wider than 0.12 mm (0.005 in.) A polar gate is the best way to overcome the difference in phase angle that occurs between natural cracks and slots. However, only a few eddy current flaw detection instruments have polar gates. If a typical horizonal gate is used, rotate the vector dot screen so that the horizonal components from equal amplitude slot and natural crack signals are equal but opposite. How the proper angular setting of both signals minimizes errors caused by a gap in the slot of a simulated crack is shown in figure 4.

Fatigue Cracks

Fatigue cracks are not to be used in reference standards for any type of non-destructive test. They are undesirable because of their uncontrolable electrical conduction.

Natural cracks can be grown to order by fatiguing. A shallow notch is cut into a metal surface, the notch is cyclicly loaded in tension, and a natural crack is grown to the depth desired. The starting notch is then machined away leaving a natural crack in the metal surface of a part.

A major problem with fatigue cracks is that a portion of the sides are in electrical contact with one another. The low order of pounding between sides, while a fatigue crack is being grown, causes a flow of metal and resultant metallic contact.

Ten fatigue cracks all the same size will probably have ten different amplitudes of eddy current test signals. All of the signals will indicate a smaller crack than actually exists. Eddy current flow across electrically conducting portions of the sides of fatigue cracks masks their true crack size.

Inside a fatigue crack there are smooth shiny sidewalls that are in electrical contact with one another.

Inside a quench crack there is a rough surface much of which is covered by a black carbonaceous coating. The black coating is from the oil that was in the quench tank. A portion of the crack, up to its apex, has no black coating as it was too tight for the quenching oil to penetrate.

Plugs

Plugs that are made from material identical to that being tested, thinly coated on their diameter with an electrical insulator (such as aluminum oxide or varnish), and then fitted into a hole can be used to simulate cracks. No record of this having ever been done has been encountered; however, it is a feasible method. Care should be taken to assure that the insulative coating is not violated when pushed into the hole.

Magnetic Flux Leakage Tests

Magnetic flux leakage testing is proving to be superior to ultrasonic testing where complex geometry prevents 100% ultrasonic coverage in two directions at right angles to one another. At present, mostly thin walled parts are involved. Magnetic flux leakage testing is being expanded to include heavier walled items such as mortar cartridge bodies and 155-mm carrier projectile bodies. It has been safely used on loaded and fuzed 40-mm M384 projectiles.

Slots

The criteria for slot sizes are the same as for eddy current testing with one exception, slot gap has no affect on test results. Since the magnetic field is generated by direct current, there are no phase angles. Never the less, it is recommended that a narrow gap of no more than 0.12 mm (0.005 in.) be maintained. The slots are sealed with a nonmagnetic, noncorrosive filler such as silicone rubber, epoxy, varnish, or paint to prevent any bridging by magnetic particles.

Plugs

The same criteria that is used for eddy current reference standard plugs also apply to plugs used in magnetic flux leakage reference standards.

A reference standard was made for 4.2-inch M329A2 mortar projectile bodies by drilling a number of holes and plugging them. A 3 mm (0.12 in.) hole was placed on the axial centerline through the bottom of the body to simulate piping. The hole was sealed with a short nylon plug. Larger holes of 12.7 mm (0.50 in.) and 19 mm (0.75 in.) were drilled in other locations of the projectile body and sealed with steel rods squeezed inside 0.25 mm (0.10 in.) thin-walled nylon bushings. The press-fitted assembly was rigid enough to withstand cleanup turning on a lathe so that the outside diameter blended in with the adjacent surface. This reference standard was designed for use with both ultrasonic as well as magnetic flux leakage testing. It performed well with ultrasonic testing, but was not used with magnetic flux leakage testing.

Accumulation Leakage Tests

In the late 1960's, a leakage test for metal ammunition boxes came under critical review. The ammunition boxes were of many different sizes and contained such items as small arms cartridges, artillery fuzes, mines, and white phosphor mortar rounds. All of the boxes were tested for leakage in the same way. They were packed, sealed, placed in a leakage accumulation chamber, and subjected to a slight pressure. The accumulation chamber was then isolated and its pressure was monitored. Thousands of loaded ammunition boxes went through this leakage test without rejection before some rusty fuzes showed in the field. Analyses of the leakage test revealed that the applied test pressure was forcing the hinged covers into the sealing rubber gaskets of the boxes and thereby masking existing leaks.

The applied pressure was changed to an applied vacuum accumulation leakage test which simulated what would occur during air transportation. Thereafter, leaking ammunition boxes were detected during acceptance test.

The vacuum accumulation leakage test is also applied to sealed flexible bags and small containers. Reference standards are needed to simulate a no leakage part, a slow leakage part, and a fast leakage part. The standards simulate the exact average volume of the parts (or bags) being tested.

No Leakage

The purpose of a no-leaker reference standard is to measure the leakage of the test equipment. For small parts, an accumulation leakage test usually involves placing the part inside a chamber, drawing a vacuum inside the chamber, and monitoring the vacuum to determine the rate of leakage from inside the part. But more than the part can leak. Maximum permissible leakage of the test equipment itself should be no more than 10% of the maximum permissible leakage of the part.

Slow Leakage

A leakage acceptance criterion would be expressed in atmospheric cubic centimeters per second for an applied vacuum differential. That is, at sea level, what maximum volume rate of air leakage would be acceptable if so many inches of vacuum were placed around the package? When establishing a leakage criterion for the package to be tested, care must be taken to assure that the package can provide the sealing protection required. If a package has already been designated and has performed acceptably in similar applications, then its leakage performance should be evaluated. Take a sample of one hundred or so packages and test them for leakage. It should be found that most of the packages will perform similarly. One or so packages may be obvious leakers. Plotting actual leakage performance should reveal a large gap between the no leakers and the leakers. It is within this leakage performance gap where the acceptance limit should be placed.

A slow leakage rejection reference standard can be made by taking a well sealed package and placing a very tiny hole in it. Then the hole must be calibrated to determine the actual rate of leakage.

Slow leakage reference standards can also be designed by incorporating a small leakage capsule into an inert simulated package. The capsule, when charged with dry gas under a specified pressure, will leak at a certified rate. They are commercially available at many different leakage rates. With a leakage capsule, no vacuum need be drawn on the slow leakage reference standard. In an accumulation chamber, pressure will slowly increase from the released gas; however, as the pressure increases, the rate of leakage diminishes.

Fast Leakage

Fast leakage of a part is usually detected during an accumulation leakage test by inability to pull a minimum needed vacuum in the chamber. The source of vacuum can be an air cylinder that removes a fixed amount of air from the chamber. If some air is rapidly available from inside a fast leaking part, the vacuum pulled inside the chamber will not reach the minimum amount needed.

A fast leaker reference standard is best made from a part containing a relatively large hole. The free internal volume should be equal to that of the item to be tested.

LENGTHS OF SLOTS

Nondestructive tests for structural integrity should be designed to accurately detect the occurrence of relatively short cracks. If this is not done, short cracks of critical depth may acceptably pass through the nondestructive test (NDT). To maintain a reliable NDT, the minimum aspect ratio (length/depth) for naturally occuring cracks should be known. Assuming the minimum aspect ratio is a randomly occurring relationship that seldom occurs (i.e., it occurs irrespective of crack depth), then the most difficult natural crack to detect would be a short crack.

For scanning tests involving ultrasonic, eddy current, and magnetic flux leakage, the following relations between minimum slot length and the width of scanning energy field apply:

1. The reject slot that represents a minimum size defect has a full depth length of at least twice the smallest naturally occurring aspect ratio times the full depth of the slot. Curved ends of slots do not contribute to the minimum length.

2. The maximum effective width of the scanning energy field where the cracks are located are no more than 1/2 the length of the minimum sized reject slot.

These requirements permit the use of long continuous reject slots in reference standards without reducing the severity of the rejection criteria.

Example: What should be the minimum lengths for defect slots in reference standards for magnetic flux leakage inspection of 155-mm M549A1 warheads? Review of past data (ref 10) reveals that the minimum aspect ratio found for quench cracks in HF-1 alloy steel is 6. Therefore, the minimum full depth length of a slot in a reference standard is 2 times 6 times the depth of the slot. A 1 mm (0.040 in.) deep slot can be no less than 12 mm (0.48 in.) long (full depth).

Example. Design a reference standard for an ultrasonic test of 81-mm M374 mortar cartridge bodies. Examination of stresses on the cartridge body structure during maximum increment charge launch reveals very low levels of tension. As a result, a through crack is the critical depth. This means a fairly deep slot is permissable for a reference standard. The minimum wall thickness of the mortar body by the tail section is around 4 mm (0.16 in.). Using a safety factor of 4, the depth of slot for simulating rejectable cracks is 1 mm (0.04 in.). The minimum length of the slot is 1-mm depth x 6 aspect ratio x 2 = 12 mm (0.48 in.) Maximum beam width of the transducer is 6 mm (0.24 in.). Beam width data from flat lensed ultrasonic transducers pulsing off a 9.5 mm (0.38 in.) precison steel ball immersed in water are listed in table 3. All of the minus 6 db beam widths are less than the criterion of 1/2 x 12 mm = 6 mm (0.24 in.). Therefore, any of the evaluated transducers can be used for this nondestructive test application.

A similar analysis would apply to eddy current testing.

Table 3. Beam widths of six various sized ultrasonic transducers with flat lenses immersed in water

Diameter of 5 Mhz active elements		Distance from a 3/8-in. steel ball for peak echo		Width of beam at minus 6 db	
mm	in.	mm	in.	mm	in.
6.35	1/4	28.4	1.12	1.5	0.06
6.35	1/4	31.8	1.25	1.5	0.06
9.53	3/8	60.5	2.38	3.3	0.13
9.53	3/8	60.5	2.38	2.3	0.09
12.7	1/2	103	4.06	3.3	0.13
12.7	1/2	132	5.18	4.8	0.19

CONCLUSIONS

The design of reference standards for nondestructive tests (NDT) is a technology in itself. Most of the work that has been done was just enough to satisfy production requirements. Much development work remains in the design of better NDT reference standards.

There are many commonalities that permit slots, round holes, and plugs to simulate cracks in different types of nondestructive tests. For many, slots are the best way to simulate cracks. Simulated cracks in NDT reference standards will continue to be popular until industry learns how to control the size and orientation of made-to-order quench cracks.

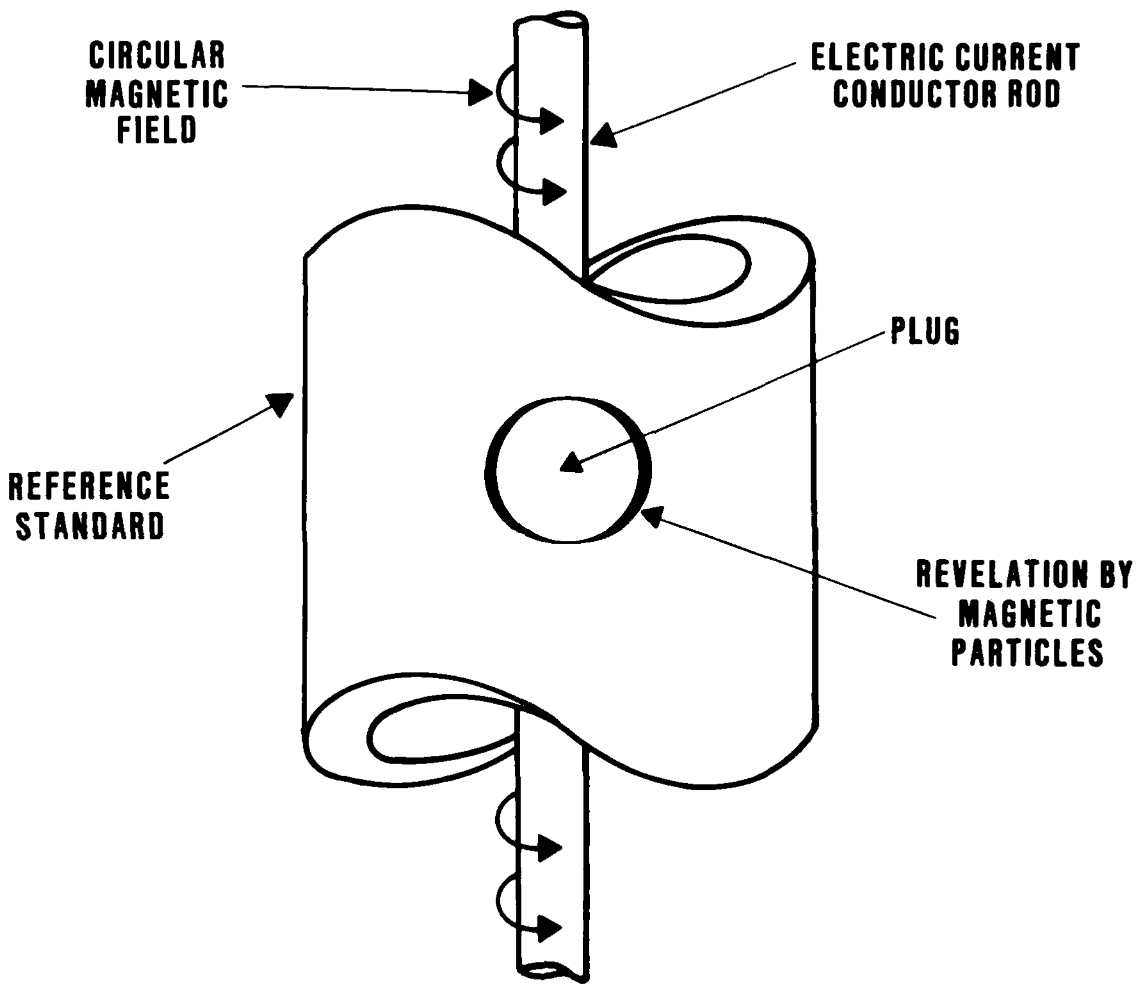


Figure 1. Plug inserted in a tubluar shaped steel part making a reference standard for a magnetic particle test

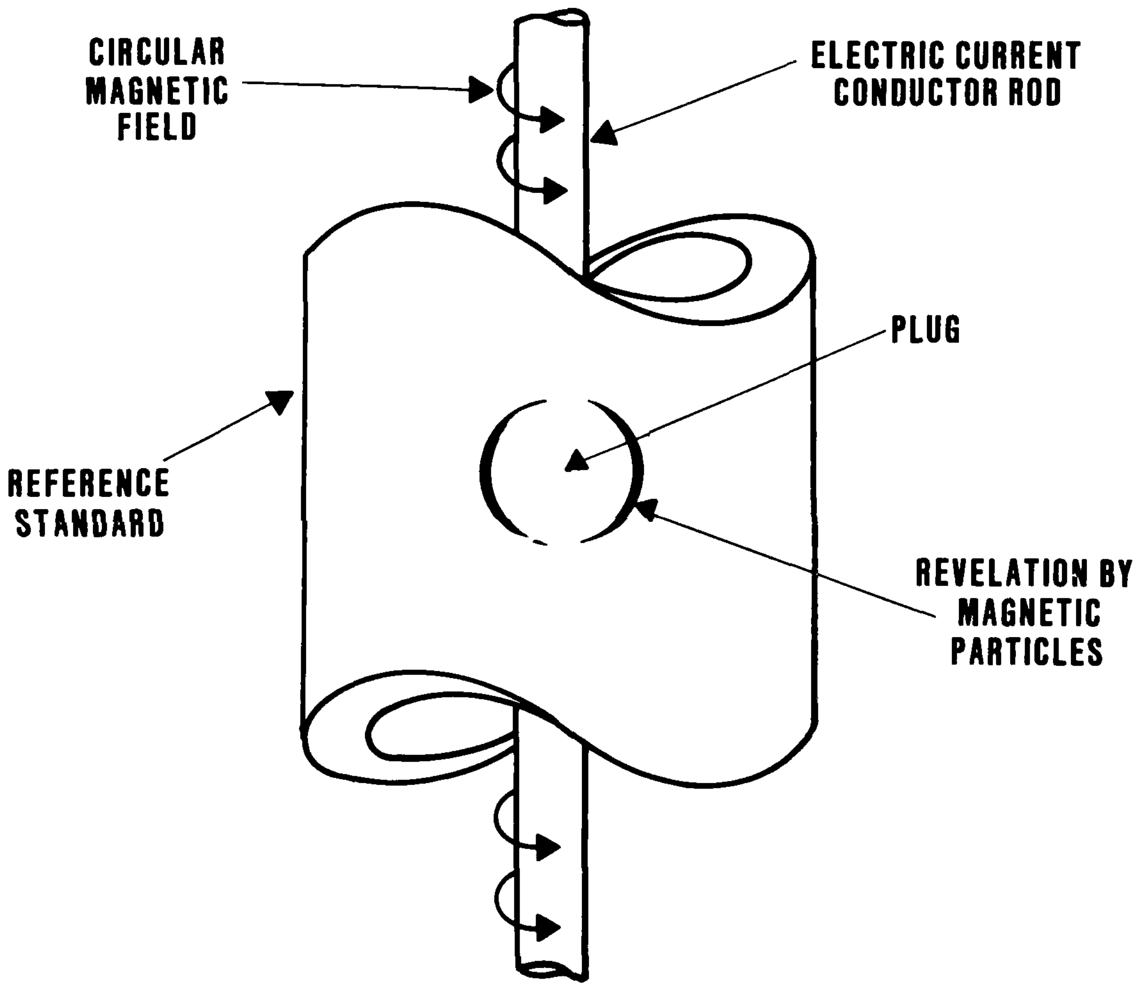


Figure 2. Revelation by a reference standard that a magnetic particle test is out of control

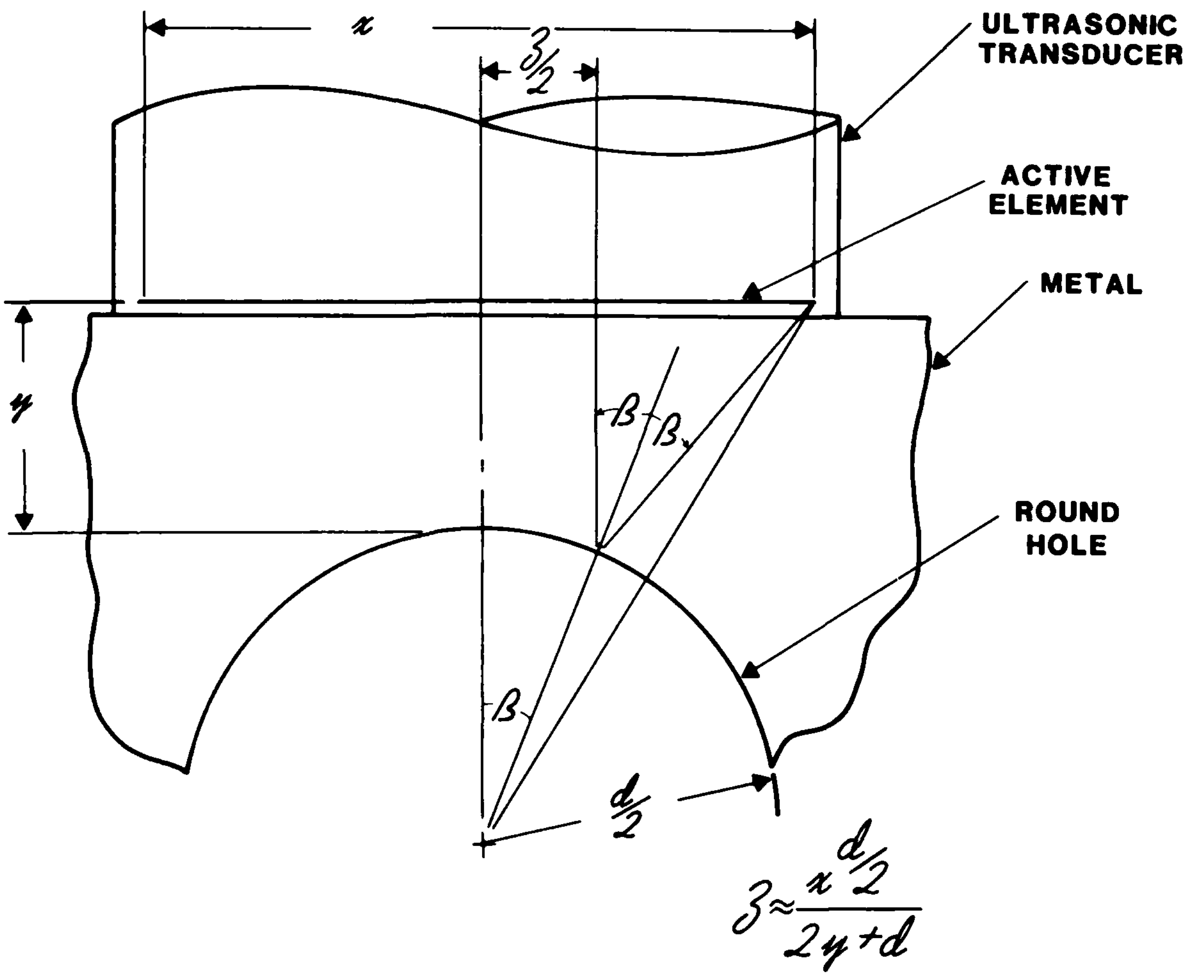
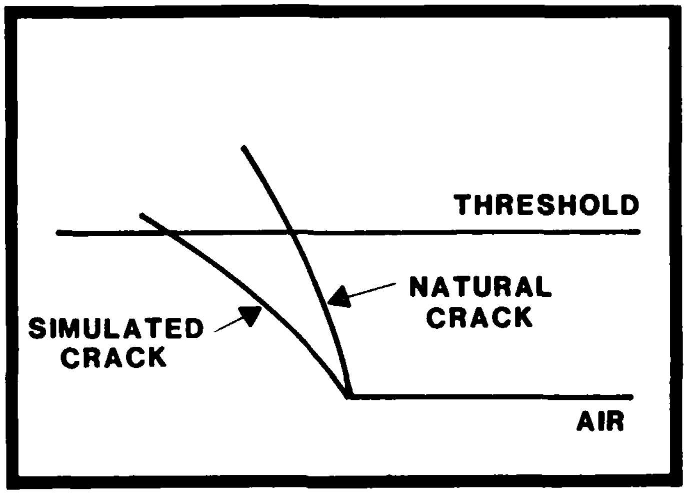
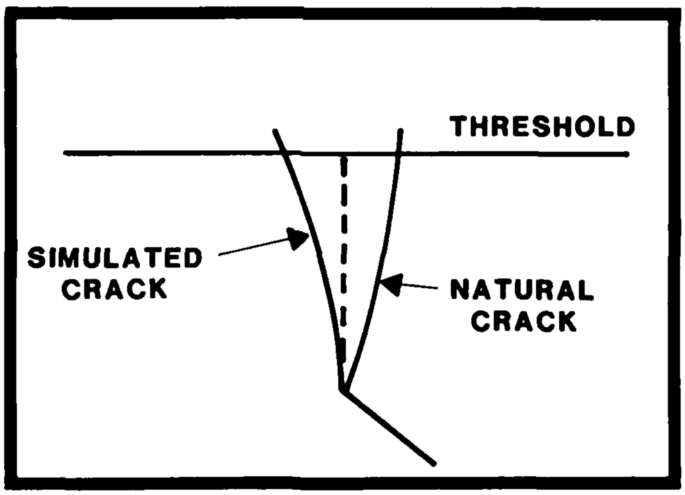


Figure 3. Reflective area from the side of a hole



IMPROPER ANGLE



PROPER ANGLE

Figure 4. Proper angle of display for a horizontal alarm threshold to minimize rejection error

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GLOSSARY

The following are the definitions of some of the words and phrases used in this report. The definitions are specific to the application intended.

Accumulation leakage test--a method of air leakage detection whereby air leakage is induced and collected inside a sealed chamber. The rate of change in monitored vacuum within the chamber reveals the rate of air leakage.

Copper crush gauge--a peak pressure measuring device consisting of a small chamber connected by an orifice to a pressure source. A small soft copper ball is placed between a hard piston and an anvil. Pressure forces the piston against the ball. The diameter of the flat on the copper ball is directly related to the peak pressure that was generated.

Crack--a narrow break, a fissure.

Defect--a discontinuity or group of discontinuties which produce indications that do not meet a specified acceptance criteria.

Discontinuity--an interruption in material which may or may not have undesirable connotations.

Eddy current testing--a nondestructive test (NDT) whereby a monitored oscillating magnetic field is directed into electrically conductive material within which oscillating electric currents moving in circular paths are generated. The magnitude of magnetic field feedback can be used to sort metals, measure differences in electrical conductivity and magnetic permeability, and detect the presence of flaws.

Electrical conductivity--the ease with which free electrons flow within material, across junctions, or through circuits.

Fatigue crack--a narrow break induced by repeated tensile and/or shear stress.

HF-1 steel--a high strength, high carbon content steel containing no war reserve alloys. This steel was developed by Bethlehem Steel Corporation for the U.S. Government free of charge.

Ketos--an oil hardening tool steel made by Crucible Steel Company.

Liquid penetrant testing--an NDT where tight surface defects in materials can be revealed by applying a dye-containing, high-capillary-action liquid which enters tight defects and amplifies their shapes by the bright color of its dye.

Magnetic flux leakage test--an NDT where discontinuties on surfaces or within the walls of ferromagnetic material are detected by applying a direct current saturating magnetic field and scanning one wall surface for deflections in the applied magnetic field.

Magnetic particle test--an NDT where flaws on surfaces or within walls of magnetizable material are outlined by the congregation of minute, mobile, magnetic particles. The particles are coated with either pigment or dye for high visibility. The particles are attracted to deflections in a magnetic field that are caused by the presence of discontinuities.

Magnetic premeability--the ease with which a magnetic field or flux can be set up in a magnetic circuit. A value of one (for air, vacuum, and water) designates great difficulty. Much higher values (in the thousands for iron) designate ease.

Martensite--A common constituent of rapidly cooled steel. It is a highly stressed structure supersaturated with carbon and is strong, hard, and brittle.

Nondestructive--no injury to, no alteration of.

Polar gate--a circular threshold surrounding the source of a signal on a cathode ray tube screen where any signal exceeding the circular threshold triggers an alarm.

Munitions--the expendable, damage-inflicting portion of weapon systems (e.g., cartridges, projectiles, bombs, grenades, mines, etc. are all munitions for tank, howitzer, bomber, infantry man, helicopter, etc.).

Proof testing--a test of strength where the strength of an item is physically tried close it its breaking point.

Quench crack--a narrow break caused by localized tensile and/or shear stresses which exceed the strength of the material. Quench cracks usually occur during heat treatment when a red hot part is rapidly cooled.

Radiography test--an NDT where exeedingly short wave-lengths of energy (x-rays, gamma rays) or atomic particles (neutrons, protons, and electrons) are used to penetrate opaque materials and record images on film (a radiograph) or on a photosensor.

Reference standard (measurement standard)--a measuring system or artifact that fixes a correlation with defects of interest in a particular part so that NDT equipment can establish and maintain accuracy.

Reject--unwanted, refused.

Scanning--to examine the surface or full depth of a part by continuous coverage over adjacent small portions.

Sensitivity--a measure of the ability of an ultrasonic system to detect small discontinuities. The same concept also applies to other types of NDT.

Ultrasonic flaw detection test--an NDT where high frequency sound pulses are directed through a material. Encountered discontinuties will reflect back part of the ultrasonic pulse. The presence of discontinuties can be detected by monitoring either reflected pulses or reduced pulse transmission through a material.

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