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SUMMARY OF NONDESTRUCTIVE TESTING THEORY AND PRACTICE

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16. Abstract

The ability to fabricate design-critical and man-rated aerospace structures using materials near the limits of their capabilities requires a comprehensive and dependable quality assurance program. The quality assurance program must rely heavily on nondestructive testing methods for thorough inspection to assess properties and quality of hardware items. A survey of nondestructive testing methods is presented to provide space program managers, supervisors and engineers who are unfamiliar with this technical area with appropriate insight into the commonly accepted "nondestructive testing methods" available, their interrelationships, uses, advantages and limitations. Primary emphasis is placed on the most common methods: liquid penetrant, magnetic particle, radiography, ultrasonics and eddy current. A number of the newer test techniques including thermal, acoustic emission, holography, microwaves, eddy-sonic and exo-electron emission, which are beginning to be used in applications of interest to NASA, are also discussed briefly.

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INTRODUCTION

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CHAPTER I

INTRODUCTION

This report surveys nondestructive testing (NDT) methods of interest to NASA Launch Vehicle and Propulsion Programs. It is intended to familiarize program managers, supervisors, and engineers with available NDT methods, their uses, capabilities, and limitations. Sufficient technical detail has been provided to permit interfacing with NDT specialists and to aid in formulating management and engineering decisions regarding applications and the need for additional research and development.

Definition

A nondestructive test is any method of evaluating material and component characteristics without altering them or affecting component serviceability. Broadly, such tests are used to measure dimensions, detect flaws and defects, determine structural integrity, or determine the physical and mechanical properties or condition of an item. Nondestructive testing methods incorporate the use of indirect probing techniques. Thus, measuring the length of a metal bar with a scale is not an NDT test, but determining its length by timing the passage of an ultrasonic pulse through the bar is. To differentiate further, hydrostatic burst testing provides a direct indication of the serviceability of a pressure vessel by the imposition of conditions that simulate operation; it is not classed as an NDT test. Radiography of pressure vessel welds is an NDT test because quality assurance data are obtained indirectly by observing the behavior of an independent probing medium.

Scope

Only those methods considered as standard nondestructive tests are reported. Tests in which a material or component is subjected to direct measurement or a simulated service condition are too numerous and varied to be included.

The following five most commonly used nondestructive testing methods are emphasized in this report:

- Penetrants (Chapter III)
- Magnetic Particles (Chapter IV)
- Radiography (Chapter V)
- Ultrasonics (Chapter VI)
- Eddy Currents (Chapter VII).

Newer nondestructive testing methods (thermal, acoustic emission, holography, microwaves, and eddy-sonic) are discussed briefly in Chapter VIII. These methods are frequently useful in evaluating materials and components for which standard tests are inadequate.

Rapid advances in nondestructive testing are being made and new techniques are being constantly developed and evaluated. Because of their preliminary status and limited applicability, the inclusion of these techniques is beyond the scope of this report. Such developments should be followed closely by NDT specialists.

NDT Method Requirements

Nondestructive tests are based on the interaction of a probing medium with the defect or material characteristic of interest. A successful NDT method must satisfy two basic requirements:

(1) The defect or material characteristic of interest must be capable of affecting the probing medium.

(2) The inspection environment and hardware configuration must permit the occurrence and observation of such interactions.

Thus, liquid penetrants are used for the detection of surface defects only, because the penetrant must enter the defect. Similarly, ultrasonic testing is used to detect internal cracks. However, severe attenuation of the ultrasonic energy before it reaches the defect location must not occur as the result of the acoustic properties of the object being tested.

To conduct a worthwhile nondestructive test, the following information is also required: (1) the type of defect to be detected or the material characteristic to be evaluated, and (2) the basis for acceptance and rejection, and (3) the critical areas to be examined.

Adequate standards are required for each nondestructive testing procedure. The performance standard is used to indicate the ability of a specific method to fulfill the inspection requirements; the calibration standard is used in establishing instrument parameters to ensure reproducible results. Ideally, a piece of material identical to that being tested is used as the performance standard; as a minimum, the defect or material characteristics of interest should be present in the standard to the degree corresponding to the maximum acceptance levels. In the case of defects, they may occur naturally or they may be artificially produced. Since the ideal standard is often difficult or impossible to obtain, standards simulating the ideal are frequently used.

The calibration standard may be any specimen with a condition that permits the inspection system to be reestablished to settings determined with the performance standard. The calibration standard need not resemble the material or defect condition being evaluated. It is often practical to have one specimen that serves as both a performance and calibration standard.

CHAPTER II

APPLICABILITY OF NONDESTRUCTIVE TESTING

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APPLICABILITY OF NONDESTRUCTIVE TESTING

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CHAPTER II

APPLICABILITY OF NONDESTRUCTIVE TESTING

Introduction

Nondestructive testing and inspection procedures are used to (1) assure the quality of materials, components, and assemblies, (2) provide information for the control of manufacturing operations, (3) evaluate materials and components during service, and (4) support research and development activities. While a nondestructive testing method can be selected to achieve these objectives, it may not accomplish all of them with equal facility. X-radiography can be advantageously used for quality control purposes and for providing the information required to guide research and development efforts. However, its use on the production line for process control may be inconvenient and costly, if it is necessary to halt the line to conduct an inspection or test. In such a case, it may be advisable to use another radiographic technique or another process to obtain the required data. Because of process requirements, it may be equally difficult to X-ray materials and components under field conditions.

Thus, a nondestructive testing method must be selected on the basis of the application as well as its inherent capabilities. Because of method limitations, inspection environment, and hardware configuration, it may be necessary to use several complementary methods to obtain the required data.

In this section, the general applicability of nondestructive testing methods dicussed in this report are presented in matrix tables. It should be emphasized that these tables can serve only as a guide and that the respective chapters covering each method should be consulted for more details. Ultimately, experienced NDT personnel must make the final selection of the test method or methods.

Table II-1 contains a brief description of the basic characteristics of each NDT method covered in this report. Tables II-2 and II-3 contain ratings of applicability of NDT methods for the detection of various types of defects and conditions in solid metallic and nonmetallic materials, respectively. Table II-4 contains ratings of applicability of NDT methods for testing composite and honeycomb materials, both metallic and nonmetallic. In these tables, the presence of a blank column indicates that the NDT method has been considered but it is not suitable for the intended application.

In rating the applicability of methods, the use of special techniques discussed in the text for enhancing the utility of each method was considered. Thus, the ability to detect small, tight surface cracks (planar defects) with penetrants was rated on the basis of using the best available technique (e.g., stressing the part to open cracks so that the penetrant can enter them). Similarly, for detecting small surface cracks by ultrasonics, the use of surface waves was assumed. Such techniques, of course, are not always applicable. If a distinctly different technique from that implied by the broad generic name of the method listed was considered in a rating, it

TABLE II-1. BASIC CHARACTERISTICS OF NDT METHODS

Method	Chapter	Characteristics
Penetrants	III	Uses a colored or fluorescent dye suspended in a liquid to detect open surface-connected discontinuities.
Magnetic Particles	IV	Uses a magnetic field to detect surface or near-surface discontinuities in ferromagnetic materials.
Radiography	V	Uses penetrating radiation to detect discontinuities or to determine material characteristics and properties.
Ultrasonics	VI	Uses high-frequency sound waves to detect discontinuities or to determine material characteristics and properties.
Eddy Currents	VII	Uses induced alternating electrical currents to detect discontinuities or to determine material characteristics and properties.
Thermal	VIII	Uses measurement of surface heat distribution to detect surface or near-surface discontinuities.
Acoustic Emission	VIII	Uses high-frequency sound generated by a material under stress to detect propagating discontinuities.
Holography	VIII	Uses coherent light to detect surface or near-surface discontinuities.
Microwaves	VIII	Uses radiated electromagnetic energy to detect voids or to determine material properties and characteristics.
Eddy-Sonics	VIII	Uses high-frequency sound waves produced by induced alternating electrical current to detect discontinuities.

TABLE II-2. APPLICABILITY OF NDT METHODS TO METALLIC MATERIALS

Defect or Material Condition	Examples	Qualifying Conditions			Liquid Penetrant	Magnetic Particle	X-Ray	Gamma-Ray	Fluoroscopic Techniques	Pulse Echo	Through Transmission	Resonance	Eddy Current	Thermal	Accoustic Emission	Holography	Microwave	Eddy - Sonic
Chapter					III	IV	V			VI			VII	VIII				
							Radiography			Ultrasonics				Other Methods				
Voids	Porosity in welds; Gas pockets and blow holes in castings	Surface	Shallow		F	P	F	F	P				F	P		P	F	
			Deep		G	G	G	G	F	F			G	F		F		
		Near surface				F	G	G	F	P			F	P				
		Internal					G	G	F	G	F							
Planar Parallel to surface	Laminar oxide layer in plate; Rolled-out void in plate; Cracks in welds	Near surface	Tight/open				P	P	P	P	G			/G	G	G		
		Internal					P	P	P	G	G			P	G			
Inclusions	Foreign metal particle contamination; Tungsten in welds	Surface	Metallic inclusions	Tight/loose	P/G	G	$G^{(2)}$	$G^{(2)}$	$F^{(2)}$	G			P	/F				
		Near surface					$G^{(2)}$	$G^{(2)}$	$F^{(2)}$	P	F		P					
		Internal					F	F	$F^{(2)}$	G	F							
	Slag inclusions in welds	Surface	Nonmetallic inclusions	Tight/loose	P/G	G	G	G	F	G			G	G			F	
		Near surface				F	G	G	F	P	F		G	F				
		Internal					G	G	F	G	F							
Planar Not parallel to surface	Lack of penetration in welds; Lack of fusion in welds; Cracks in welds; Undercutting in welds; Tears in forgings; Seams in tubing and wire; Shrinkage cracks	Surface	Tight	Short/long	F	P/F	F	P	P	F/G			F/G	P	G	G	F	
			Open		F/G	P/G	G	G	F	G			G	G	G	G	F	
		Near surface	Short	Shallow/deep		P/F	F	F	F	F/G	G		F	P	G	F		
		Internal					F/G	F	F	F/G	G				G			
		Near surface	Long			F/G	F/G	F/G	P	G	G		F	F	G	F		
		Internal					F/G	F/G	F	G	G				G			
Thickness	Cladding thickness; Wall thickness of pipe, tubing, and pressure vessels; Paint thickness	Thick					$G^{(3)}$			G								
		Thin					$G^{(3)}$			G			G					
		Ultrathin	Coating				$G^{(3)}$						G					
			Foil				$G^{(3)}$						G					
Property or condition	Density						$G^{(3)}$											
	Stress	Surface					$G^{(4)}$									G		
		Internal								F								
	Conductivity												G					
	Elastic properties (Poisson's ratio; Young's, bulk, and shear moduli)									G	G							
	Heat treat condition												G					

SYMBOLS:
G - Good
F - Fair
P - Poor
Blank - Not applicable

(1) Magnetic material only
(2) *Density of inclusion must be substantially different from base metal*
(3) Radiometry
(4) X-Ray diffraction

NOTE: Advantageous conditions assumed in rating each NDT method.

TABLE II-3. APPLICABILITY OF NDT METHODS TO NONMETALLIC MATERIALS

Chapter					III	IV	V			VI			VII	VIII				
							Radiography			Ultrasonics				Other Methods				
Defect or Material Condition	Examples	Qualifying Conditions			Liquid Penetrant	Magnetic Particle	X-Ray	Gamma-Ray	Fluoroscopic Techniques	Pulse-Echo	Through Transmission	Resonance	Eddy Current	Thermal	Accoustic Emission	Holography	Microwave	Eddy-Sonic
Voids	Gas bubbles	Surface	Shallow		F		F		P/F					P		F		
			Deep		G		G		F	P				G		G		
		Near surface					G		P/F	P	F			F			G	
		Internal					G		P/F	F	F						G	
Planar Parallel to Surface	Delaminations	Near surface	Tight/open				P		P	P	G			F/G		G	G	
		Internal					P		P	F	G			P			G	
Inclusions	Foreign Matter Contamination of Resin Matrix	Surface	Metallic inclusions		P/G		G		F	F				G			G	
		Near surface					G		F	P	F			F			G	
		Internal					G		F	F	F						G	
		Surface	Nonmetalic		P/G		P		P					/F				
		Near surface					P		P								P/G	
		Internal					P		P								P/G	
Planar Not Parallel to Surface	Cracks Crazing	Surface	Tight	Short/long	F		P/F		P	P/F	G			P/F	F	G	F/G	
			Open		F/G		G		P	F	G			G	F	G	F/G	
		Near surface	Short	Shallow/deep			F/G		P	P/F	F			F	F	F	G	
		Internal					F/G		P	P/F	F				F		G	
		Near surface	Long				F/G		P	F	G			F/G	F	F	G	
		Internal					F/G		P	F	G				F		G	
Thickness							G(1)			G								
Density	Fuel density variations in fuel rods & plates						G(1)											
Stress		Surface														G		
Moisture																	G	

SYMBOLS:
G - Good
F - Fair
P - Poor
Blank - Not applicable

(1) RADIOMETRY

NOTE: Advantageous conditions assumed in rating each NDT method.

TABLE II-4. APPLICABILITY OF NDT METHODS TO HONEYCOMB AND FIBER COMPOSITES

Defect or Material Condition	Examples	Qualifying Conditions		Liquid Penetrant	Magnetic Particle	Radiography: X-Ray	Radiography: Gamma-Ray	Radiography: Fluoroscopic Techniques	Ultrasonics: Pulse Echo	Ultrasonics: Through Transmission	Ultrasonics: Resonance	Eddy Current	Other Methods: Thermal	Other Methods: Acoustic Emission	Other Methods: Holography	Other Methods: Microwave	Other Methods: Eddy-Sonic
Chapter				III	IV	V	V	V	VI	VI	VI	VII	VIII	VIII	VIII	VIII	VIII
Composite Fiber Condition	Fiber misalignment or omission	Orientation				G		F									
		Fiber-matrix bond failure												F			
		Broken				G		P									
Honeycomb Bond Condition	Improperly cured core-to-face sheet bonds	Strength	Adhesive								F						$F^{(2)}$
	Core-to-face sheet lack of bond	Unbonds	Near side						G		G		G		G		$G^{(2)}$
			Far side								F						$F^{(1)}$
Honeycomb Core Condition		Fractured walls				G		F			P				G		$P^{(2)}$
		Crushed walls				G		F			F				G		$F^{(2)}$
		Missing cells				G		F			G				G		$G^{(2)}$
Foreign Materials in Honeycomb	Water or foreign items in cells					G		G							$G^{(3)}$		

SYMBOLS:
G - Good
F - Fair
P - Poor
Blank - Not applicable

(1) Density of fibers must differ substantially from matrix
(2) Face sheet must be metallic
(3) Face sheet must be non-metallic

NOTE: Advantageous conditions assumed in rating each NDT method.

is noted in a footnote. For example, in rating density measurement by radiography, it was noted that the use of radiometry was considered.

The defects and conditions to be evaluated are listed according to their important geometric characteristics from an NDT viewpoint. For example, the term "voids" is used to represent three-dimensional anomalies. The defect descriptions are further qualified according to important characteristics such as proximity to a surface and the length, depth, and width (tightness) of a planar defect.

Defect description by geometric characterization instead of by name was chosen to improve the readability and usefulness of the tables. Defects having the same essential characteristics can occur in castings, welds, plate, forgings, bar, etc., and have different names in each. Listing the defects associated with each type of material would necessitate much repetition in the table and require numerous definitions of trade terminology.

Training and Certification

To ensure confidence in the results obtained by nondestructive testing and inspection, NDT personnel must be trained and certified to conduct tests in accordance with approved procedures and interpret the results in conformance with established acceptance standards. Training requirements vary according to the complexity of the equipment used for inspection and the difficulty of interpreting the results. Obviously, a higher degree of skill is needed to produce and interpret radiographs of suspected defect areas than to locate surface flaws and defects by liquid penetrant methods. Training and certification requirements are also influenced by the significance of a test, since the criteria for inspecting components whose failure might endanger a mission are more exacting than those for inspecting less important components.

NASA quality assurance training and certification requirements are detailed in NASA publication NHB 5300.4(1B), "Quality Program Provisions for Aeronautical and Space System Contractors".

Types of Defects

To interpret the results of nondestructive testing quickly and accurately, NDT personnel must be aware of the types of defects and flaws that may be encountered during inspection. Photographs illustrating the more common discontinuities are included in this report to familiarize such personnel with their appearances.(1-5)*

Cost Considerations

Nondestructive testing costs are comprised of (1) direct costs whose magnitude is either fixed or known through experience and (2) intangible costs whose magnitude depends on the specifics of the application. Since alternate methods that can be used to obtain the required data are frequently available, a cost-effectiveness analysis should be conducted to select the

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* Superscript numbers refer to References shown at the end of this Chapter.

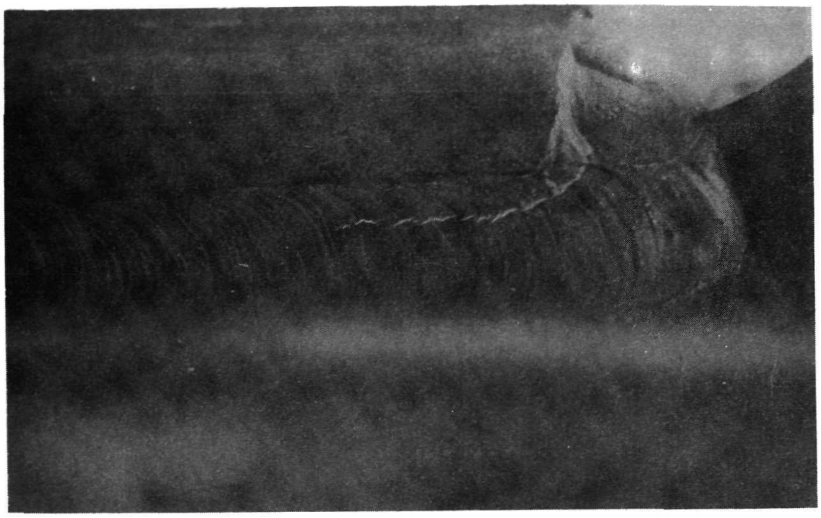


FIGURE II-1. CRACK IN WELDMENT

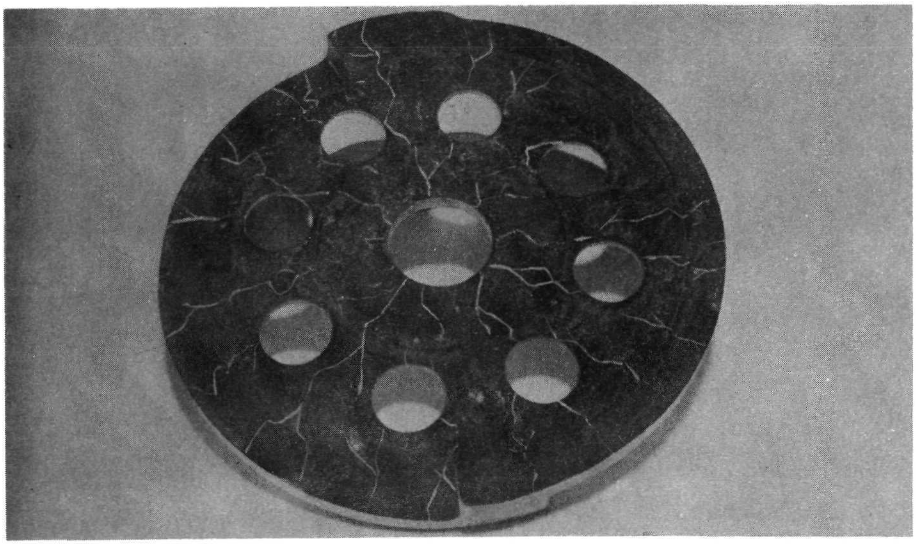
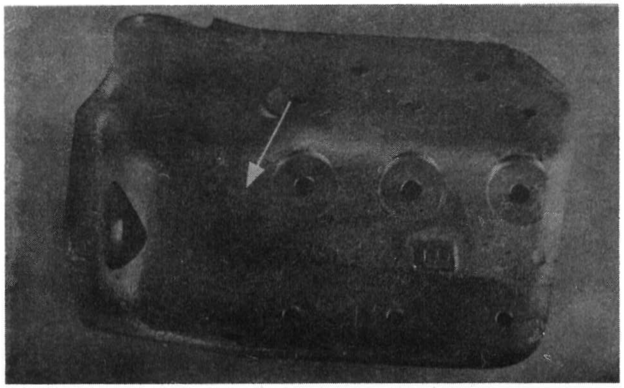
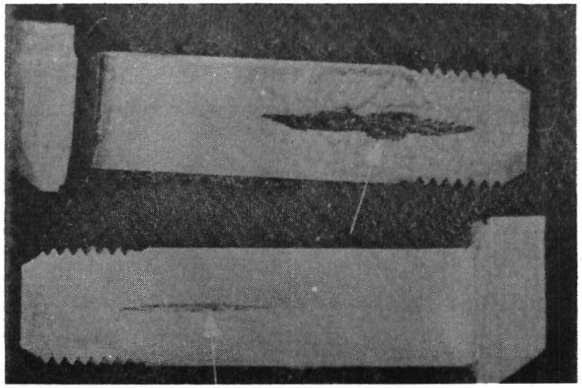


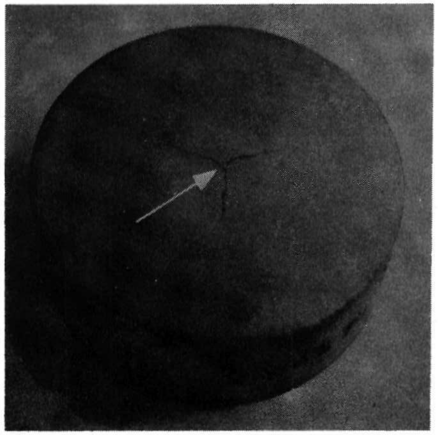
FIGURE II-2. HEAT TREAT CRACKS



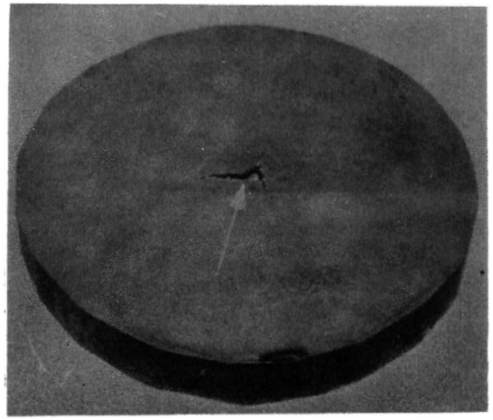
A FORGING EXTERNAL BURST



B BOLT INTERNAL BURST

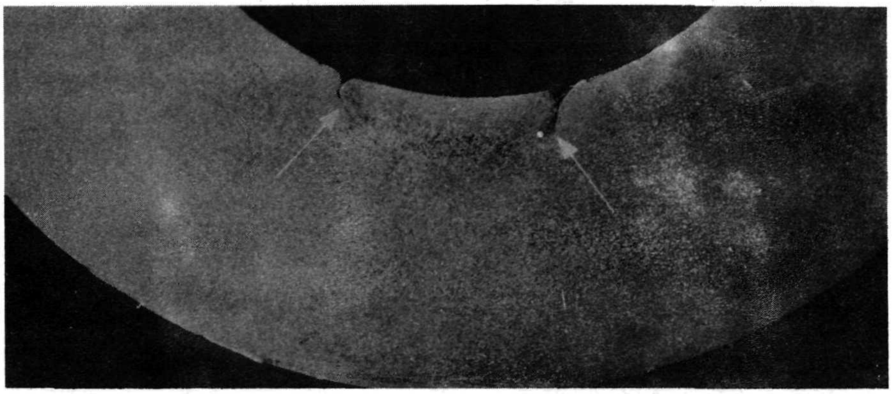


C ROLLED BAR INTERNAL BURST

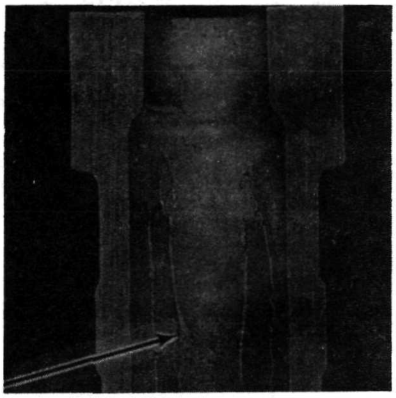


D FORGED BAR INTERNAL BURST

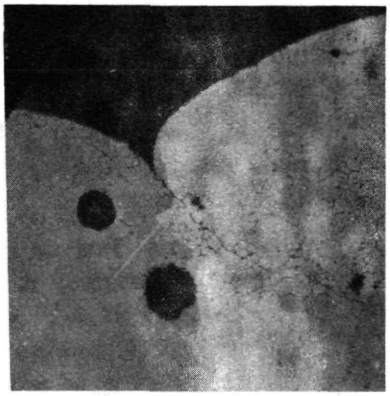
FIGURE II-3. BURST DISCONTINUITIES



A SURFACE COLD SHUT

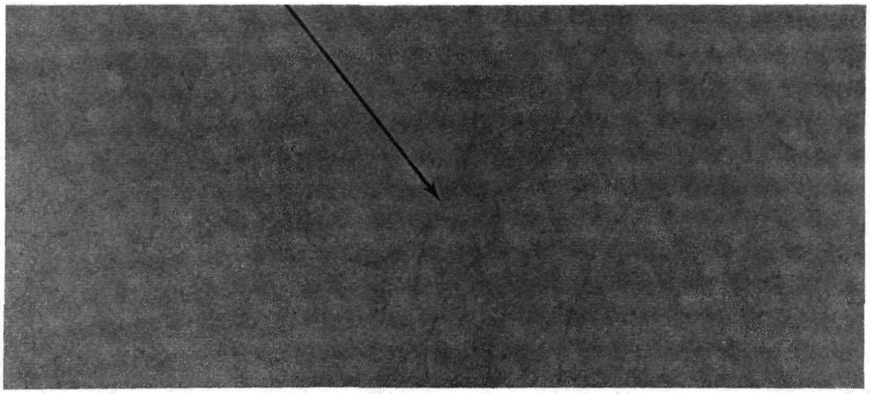


B INTERNAL COLD SHUT

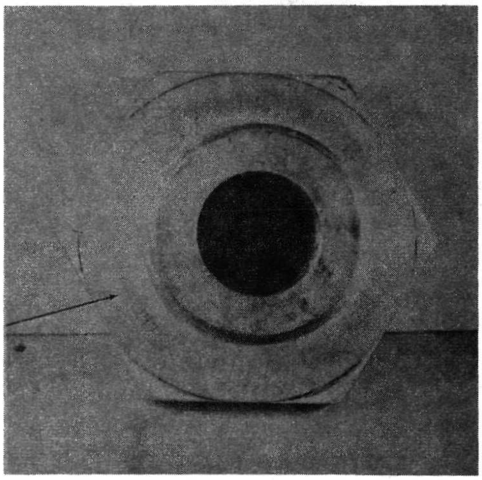


C SURFACE COLD SHUT MICROGRAPH

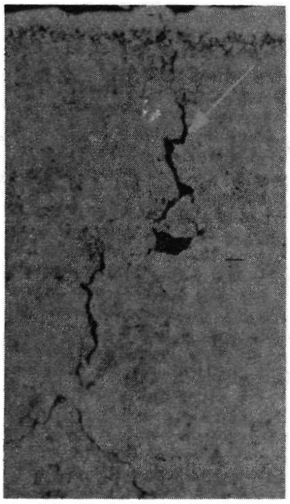
FIGURE II-4. COLD SHUTS DISCONTINUITY



A TYPICAL CHECKED GRINDING CRACK PATTERN

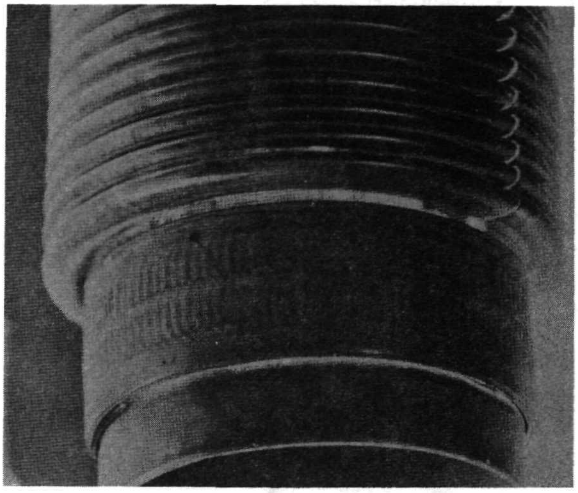


B GRINDING CRACK PATTERN NORMAL TO GRINDING

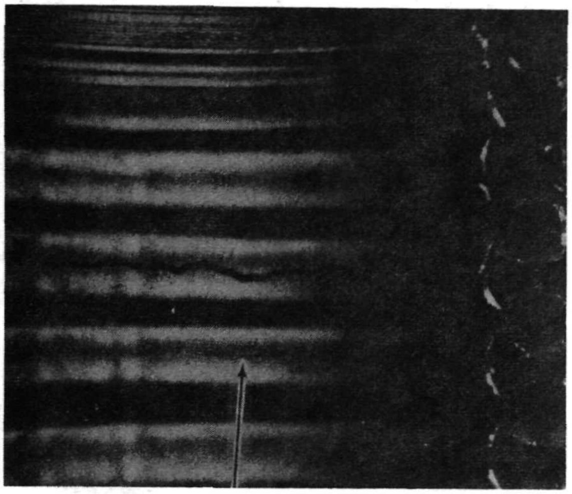


C MICROGRAPH OF GRINDING CRACK

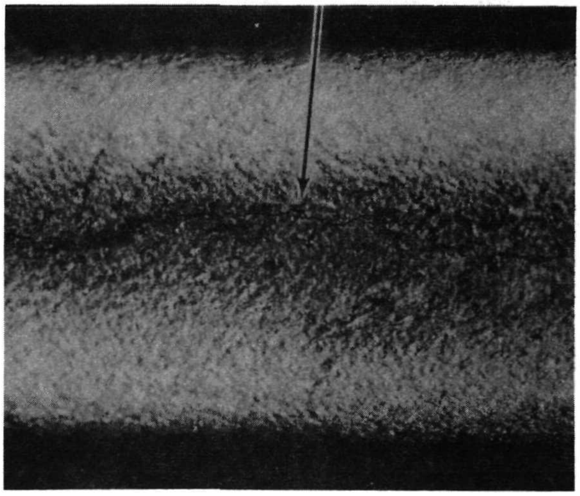
FIGURE II-5. GRINDING CRACK DISCONTINUITY



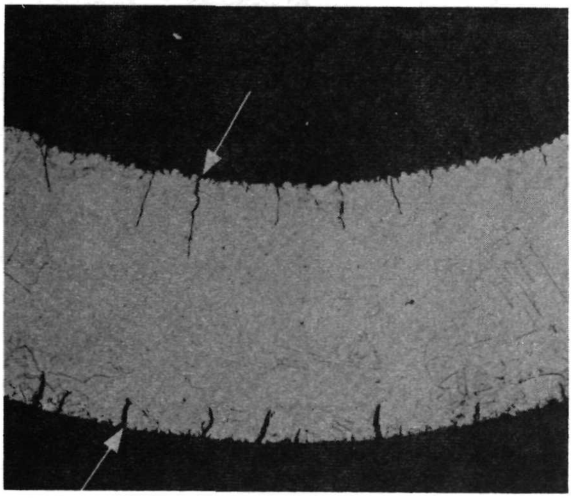
A TYPICAL CONVOLUTION DUCTING



B - CROSS-SECTION OF CRACKED CONVOLUTION

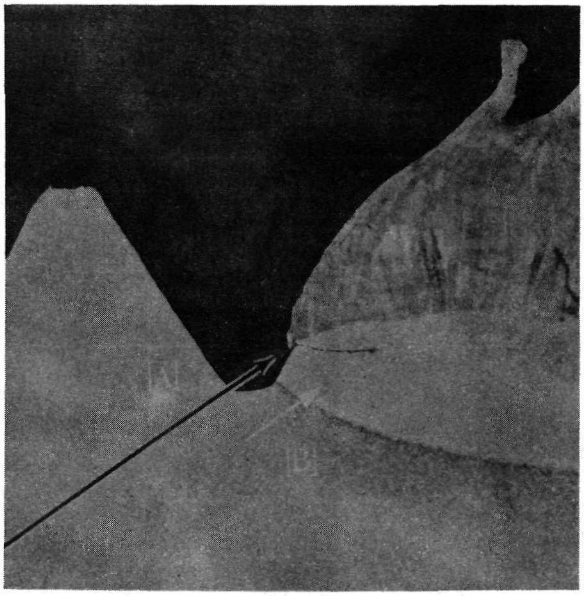


C HIGHER MAGNIFICATION OF CRACK SHOWING ORANGE PEEL

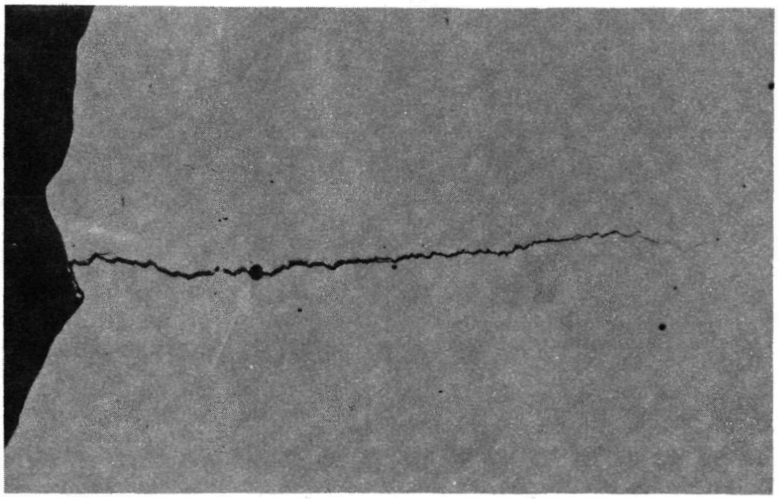


D MICROGRAPH OF CONVOLUTION WITH PARTIAL CRACKING ON SIDES

FIGURE II-6. CONVOLUTION CRACKS DISCONTINUITY



A MICROGRAPH OF WELD AND HEAT-AFFECTED ZONE SHOWING CRACK.NOTE COLD LAP WHICH MASKS THE ENTRANCE TO THE CRACK

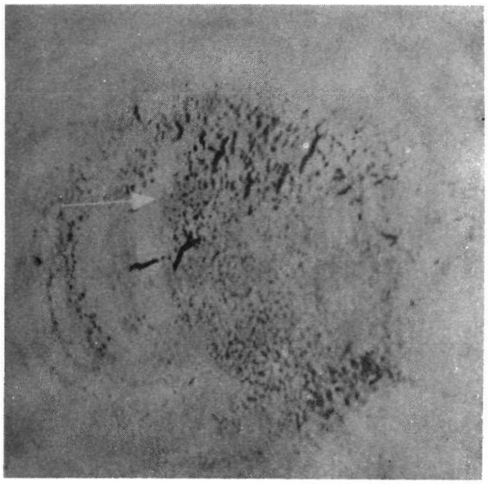


B MICROGRAPH OF CRACK SHOWN IN (A)

FIGURE II-7. HEAT-AFFECTED ZONE CRACKING DISCONTINUITY

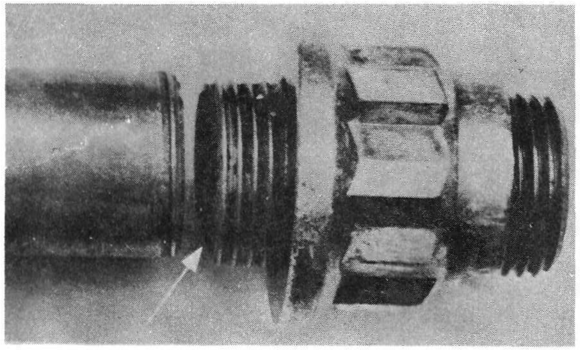
A TRANSVERSE CRACKS IN HEAT-AFFECTED ZONE

B TYPICAL STAR-SHAPED CRATER CRACK

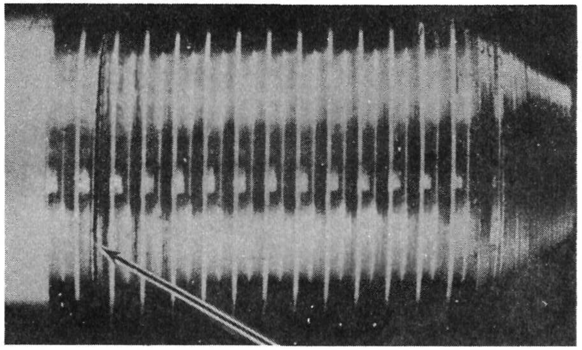


C SHRINKAGE CRACK AT WELD TERMINAL

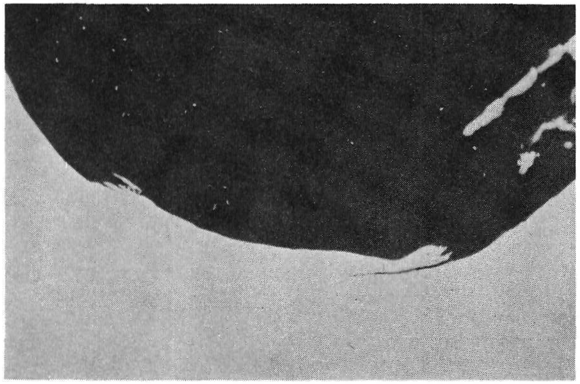
FIGURE II-8. SURFACE SHRINK CRACK DISCONTINUITY



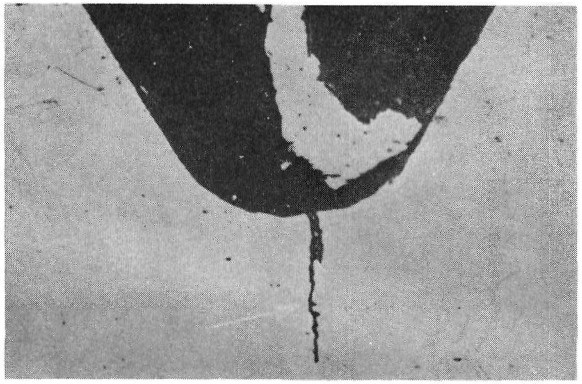
A COMPLETE THREAD ROOT FAILURE



B TYPICAL THREAD ROOT FAILURE

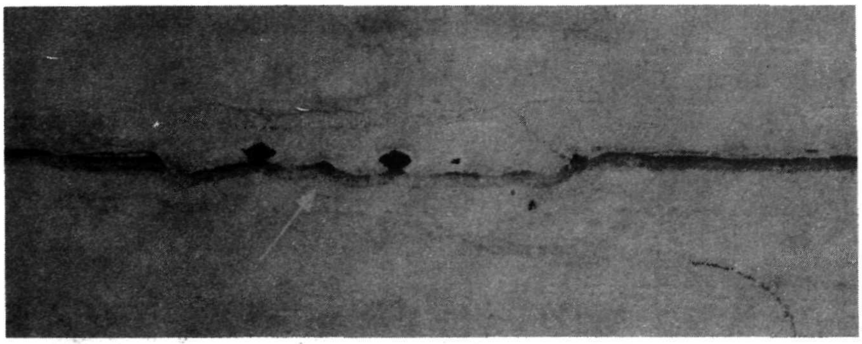


C MICROGRAPH OF (A) SHOWING CRACK AT BASE OF ROOT

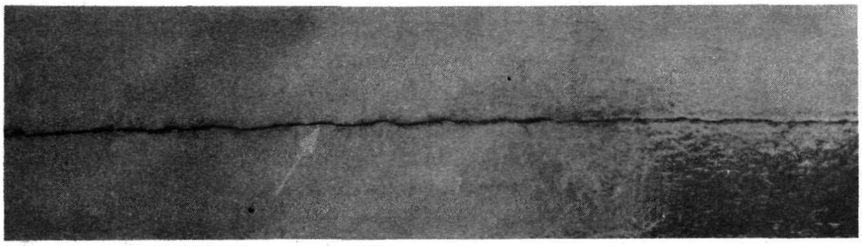


D MICROGRAPH OF (B) SHOWING TRANSGRANULAR CRACK AT THREAD ROOT

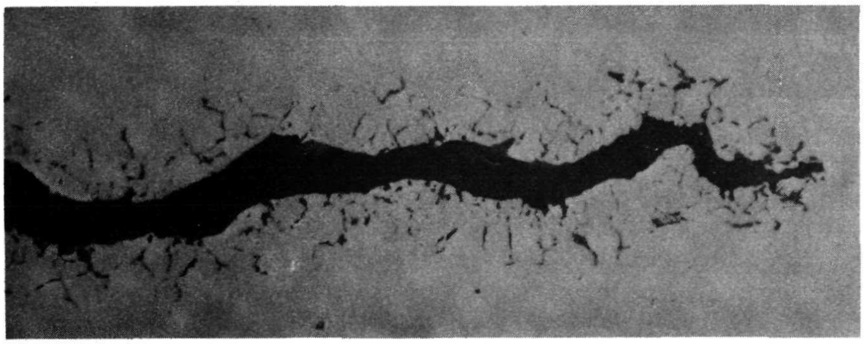
FIGURE II-9. THREAD CRACK DISCONTINUITY



A TYPICAL CRACK ON INSIDE OF TUBING SHOWING COLD LAP

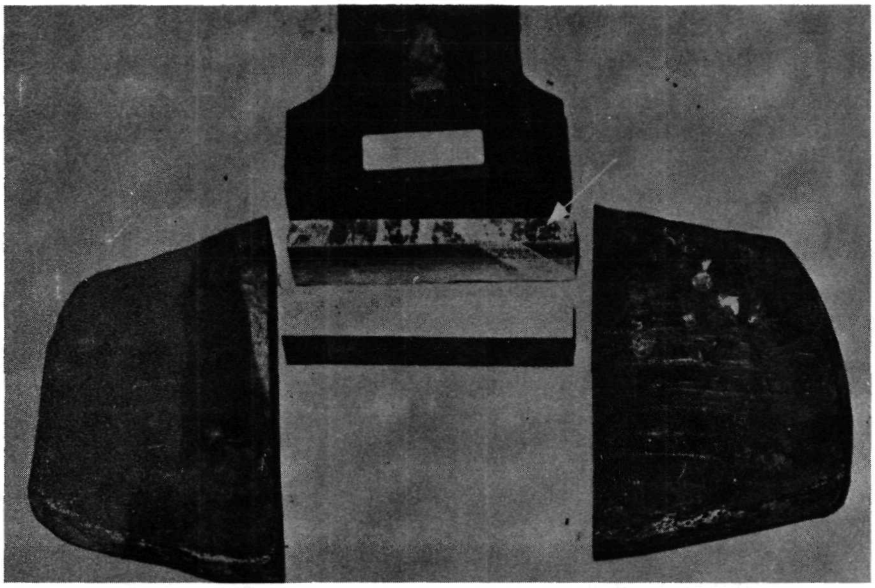


B ANOTHER PORTION OF SAME CRACK SHOWING CLEAN FRACTURE

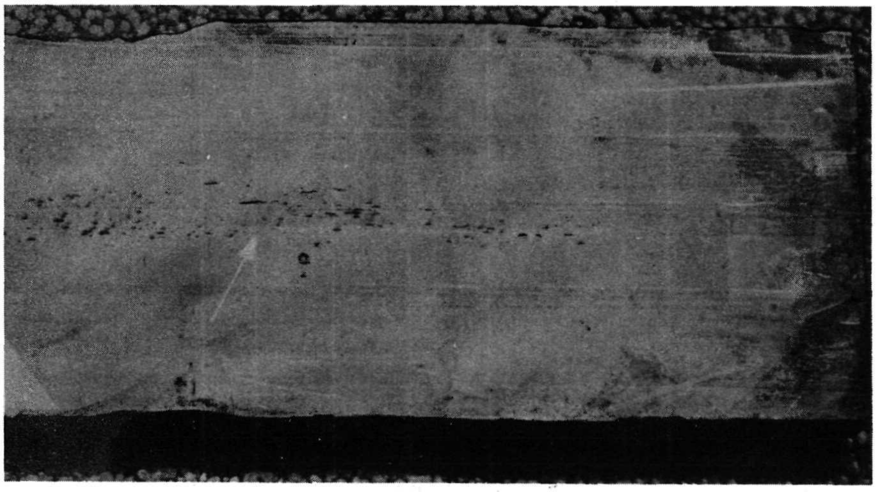


C MICROGRAPH OF (B)

FIGURE II-10. TUBING CRACK DISCONTINUITY



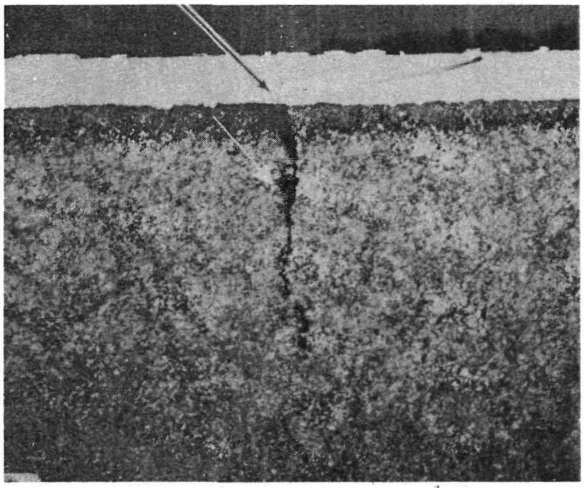
A 4340 CMS HAND FORGING REJECTED FOR HYDROGEN FLAKE



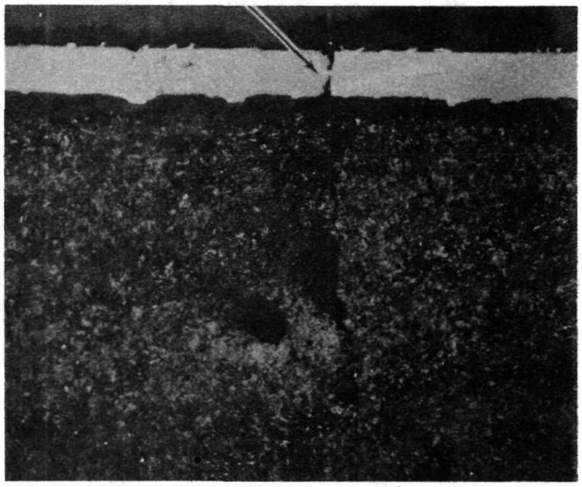
B CROSS-SECTION OF (A) SHOWING FLAKE CONDITION IN CENTER OF MATERIAL

FIGURE II-11. HYDROGEN FLAKE DISCONTINUITY

A DETAILED CRACK PATTERN OF HYDROGEN EMBRITTLEMENT

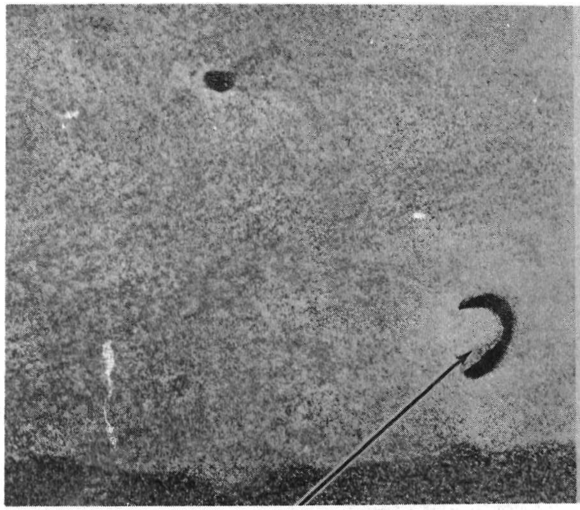


B HYDROGEN EMBRITTLEMENT UNDER CHROME PLATE

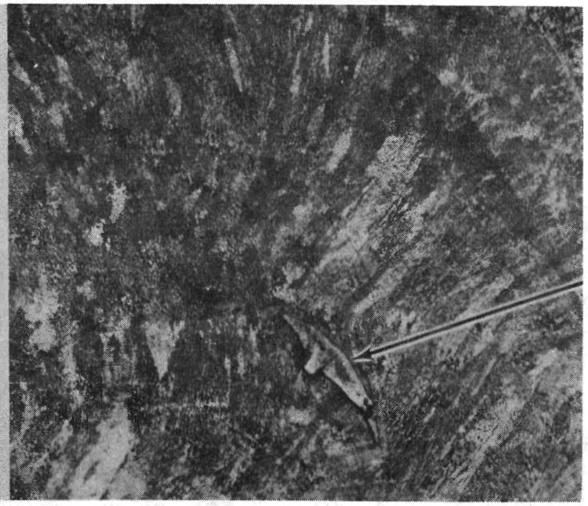


C HYDROGEN EMBRITTLEMENT PROPAGATED THROUGH CHROME PLATE

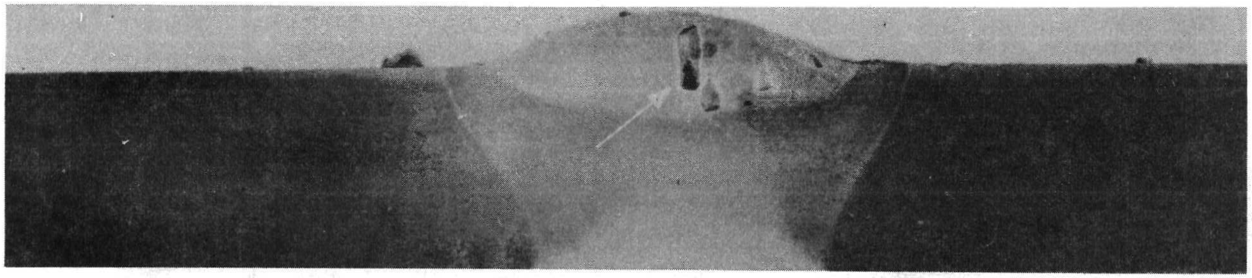
FIGURE II-12. HYDROGEN EMBRITTLEMENT DISCONTINUITY



A METALLIC INCLUSIONS

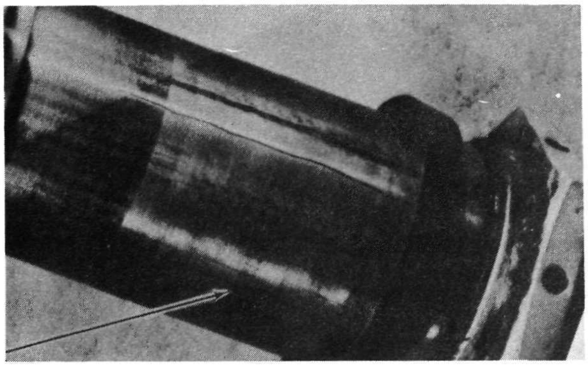


B INCLUSIONS TRAPPED IN WELD

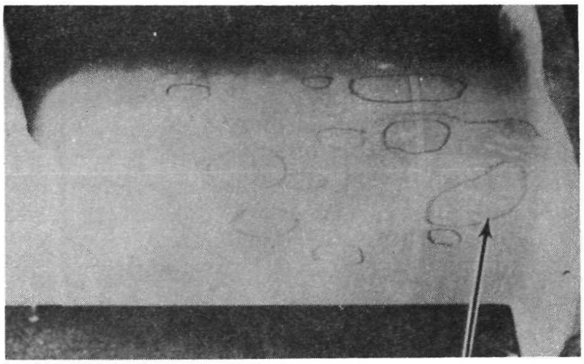


C CROSS-SECTION OF WELD SHOWING INTERNAL INCLUSIONS

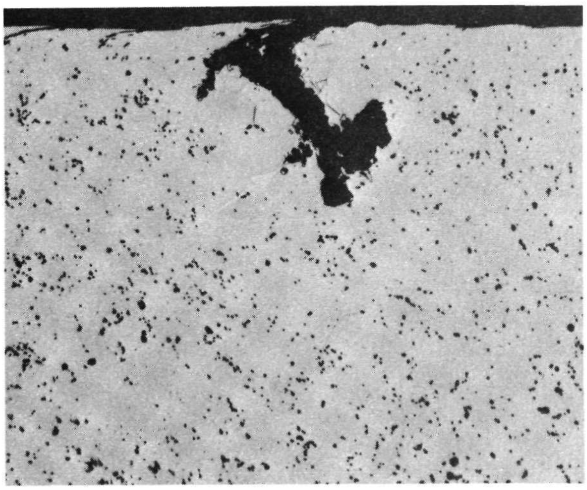
FIGURE II-13. WELDMENT INCLUSION DISCONTINUITY



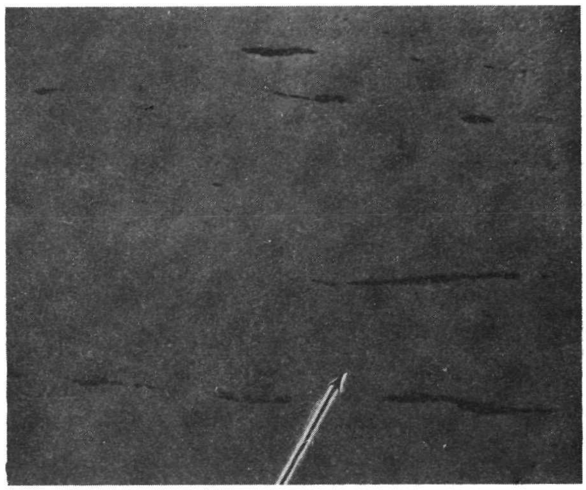
A TYPICAL INCLUSION PATTERN ON MACHINED SURFACES



B STEEL FORGING SHOWING NUMEROUS INCLUSIONS

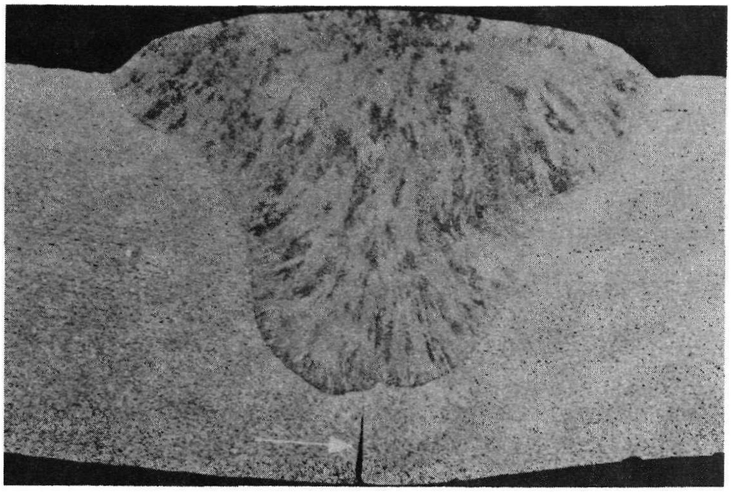


C MICROGRAPH OF TYPICAL INCLUSION

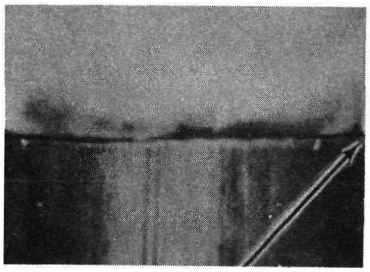


D LONGITUDINAL CROSS-SECTION SHOWING ORIENTATION OF INCLUSIONS

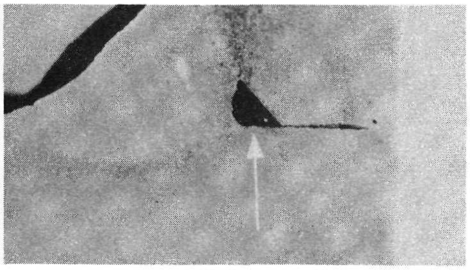
FIGURE II-14. WROUGHT INCLUSION DISCONTINUITY



A INADEQUATE ROOT PENETRATION

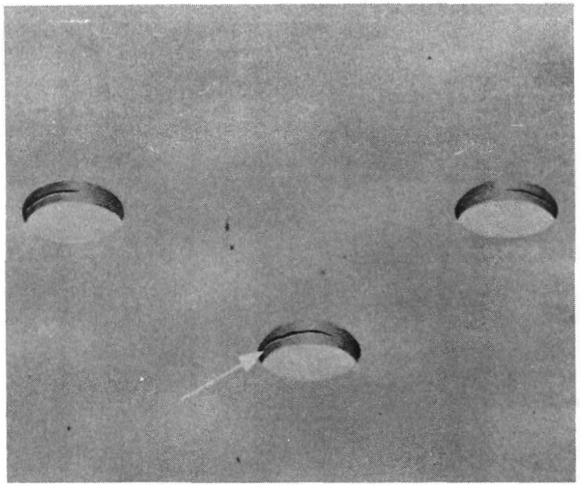


B INADEQUATE ROOT PENETRATION OF BUTT WELDED TUBE

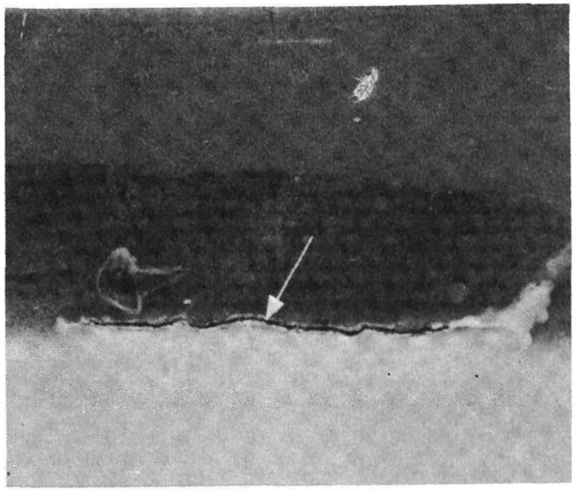


C INADEQUATE FILLET WELD PENETRATION KNOWN AS BRIDGING

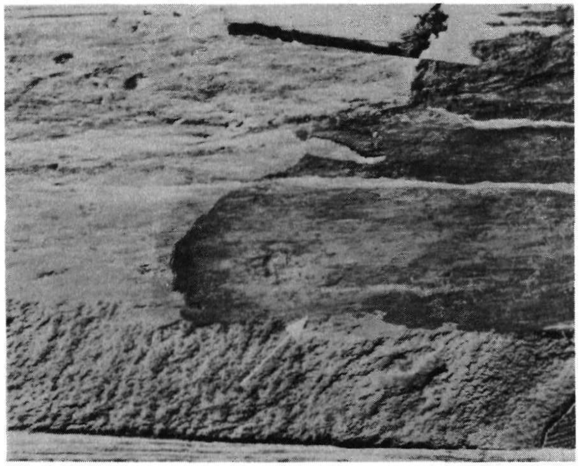
FIGURE II-15. LACK OF PENETRATION DISCONTINUITY



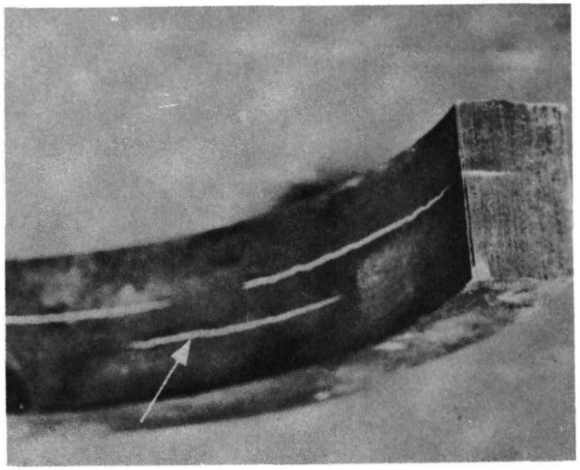
A LAMINATION IN 0.250 IN. PLATE



B LAMINATION IN 0.040 TITANIUM SHEET



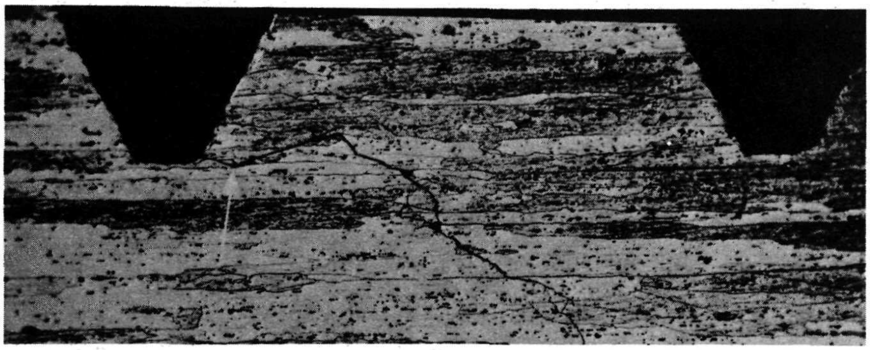
C LAMINATION IN PLATE SHOWING SURFACE ORIENTATION



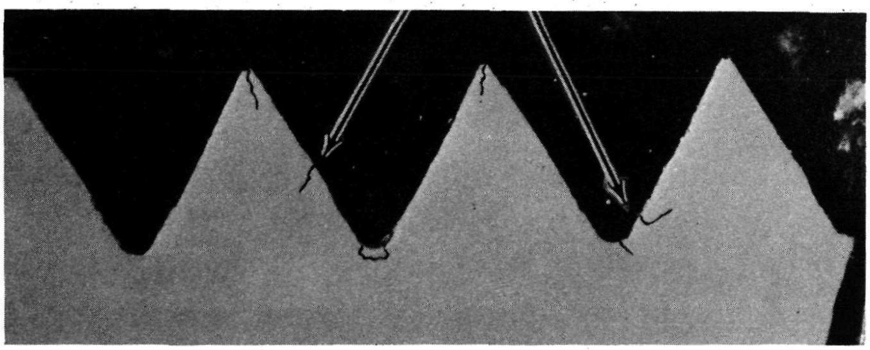
D LAMINATION IN 1 IN. BAR SHOWING SURFACE ORIENTATION

FIGURE II-16. LAMINATION DISCONTINUITY

A TYPICAL AREAS OF FAILURE LAPS AND SEAMS

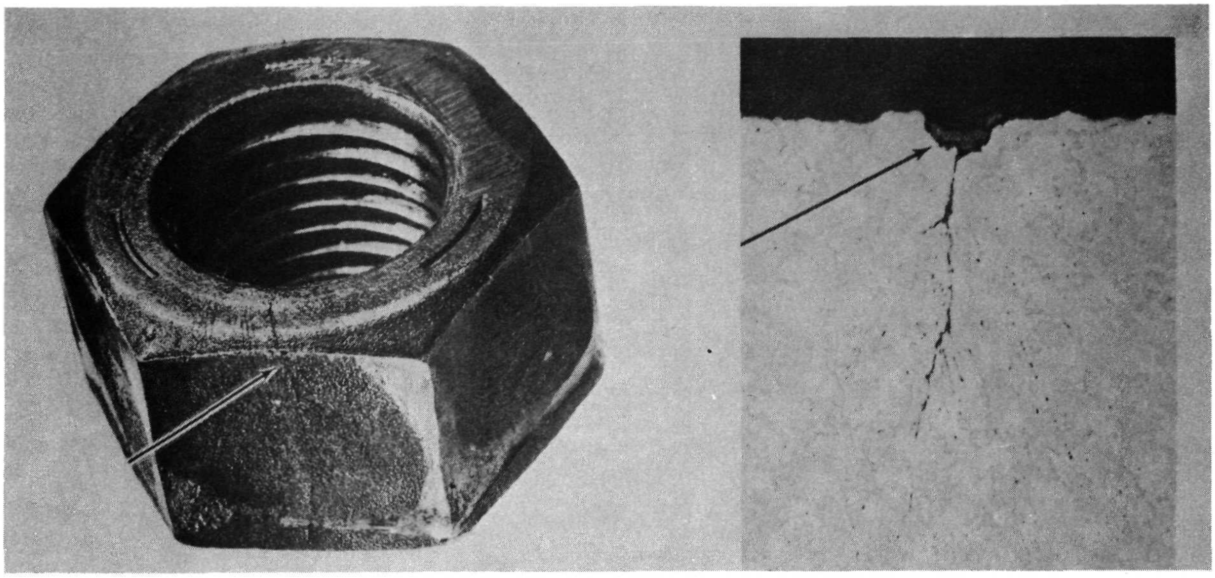


B FAILURE OCCURRING AT ROOT OF THREAD



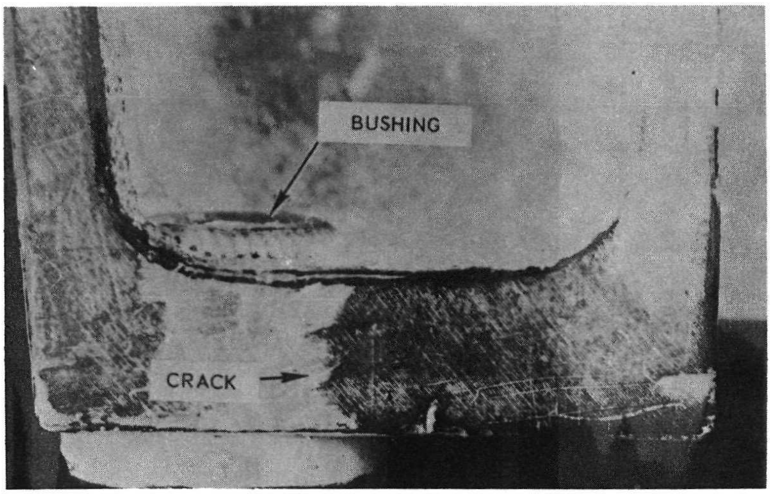
C AREAS WHERE LAPS AND SEAMS USUALLY OCCUR

FIGURE II-17. LAPS AND SEAMS DISCONTINUITY IN ROLLED THREADS

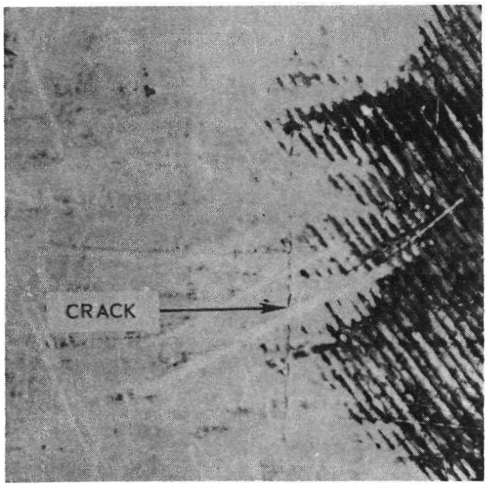


A TYPICAL FORGING LAP　　B MICROGRAPH OF A LAP

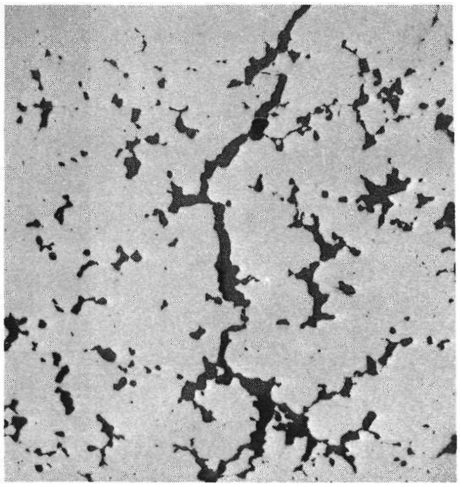
FIGURE II-18. LAPS AND SEAMS DISCONTINUITY IN WROUGHT MATERIAL



A CRACKED MAGNESIUM HOUSING



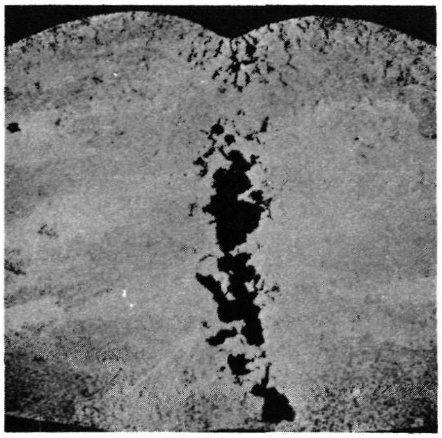
B CLOSE-UP VIEW OF (A)



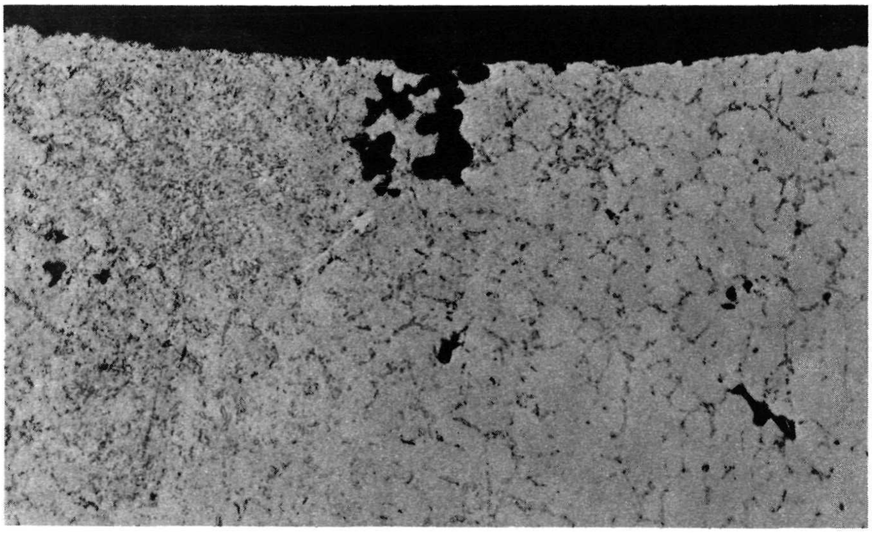
C MICROGRAPH OF CRACKED AREA

FIGURE II-19. MICROSHRINKAGE DISCONTINUITY

A TYPICAL SURFACE POROSITY

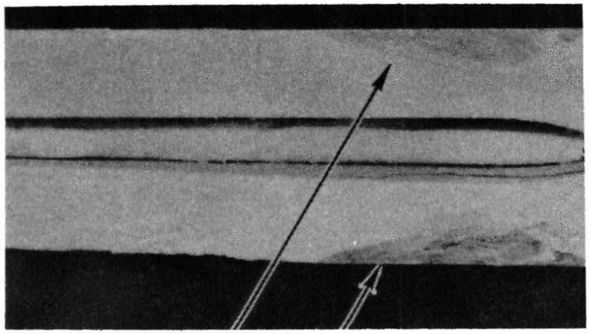


B CROSS-SECTION OF (A) SHOWING EXTENT OF POROSITY

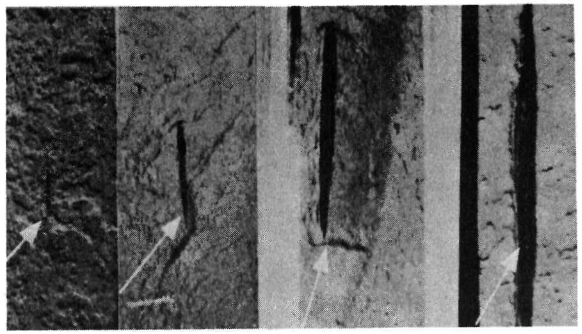


C MICROGRAPH OF CROSS-SECTION SHOWING TYPICAL SHRINKAGE POROSITY

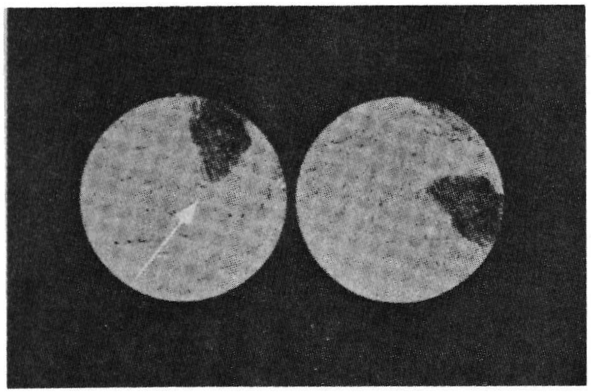
FIGURE II-20. GAS POROSITY DISCONTINUITY



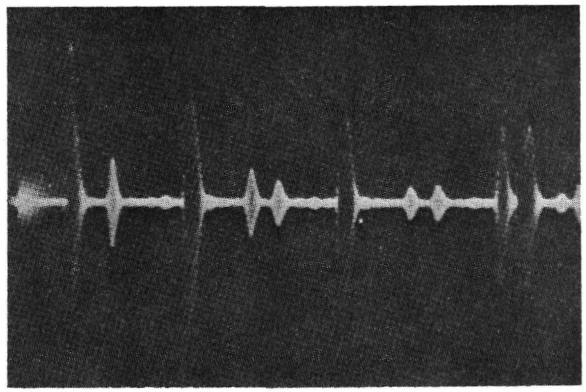
A FRACTURED SPECIMEN SHOWING UNFUSED POROSITY



B UNFUSED POROSITY EQUIVALENT TO 1/64, 3/64, 5/64 AND 8/64 (LEFT TO RIGHT)



C TYPICAL UNFUSED POROSITY



D ULTRASONIC SCOPE PATTERN OF (C)

FIGURE II-21. UNFUSED POROSITY DISCONTINUITY

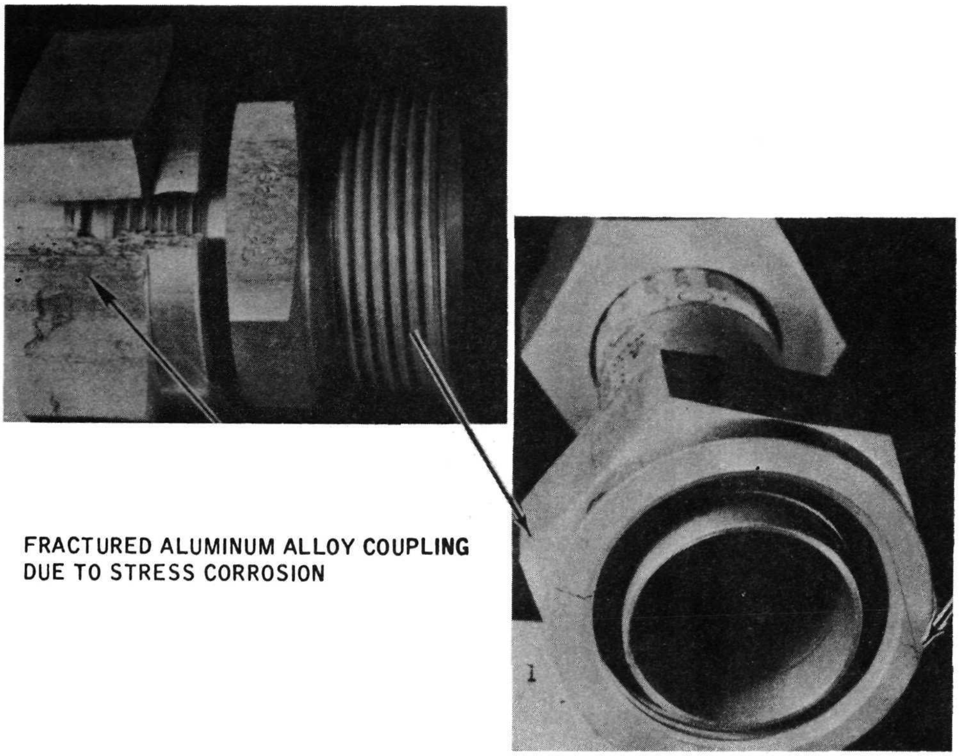
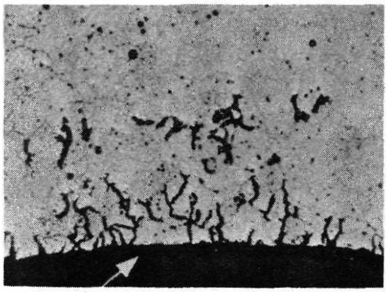
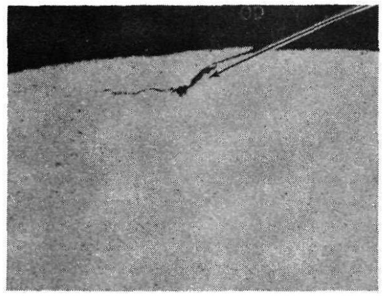


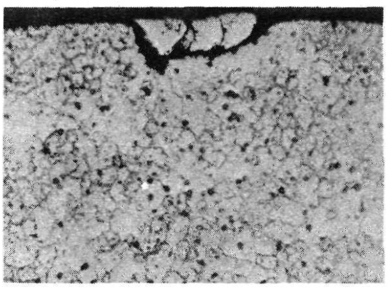
FIGURE II-22. STRESS CORROSION DISCONTINUITY



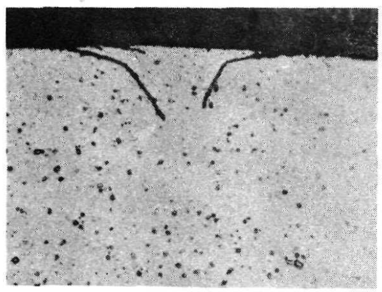
A INTERGRANULAR CORROSION



B LAP IN OUTER SURFACE OF TUBING

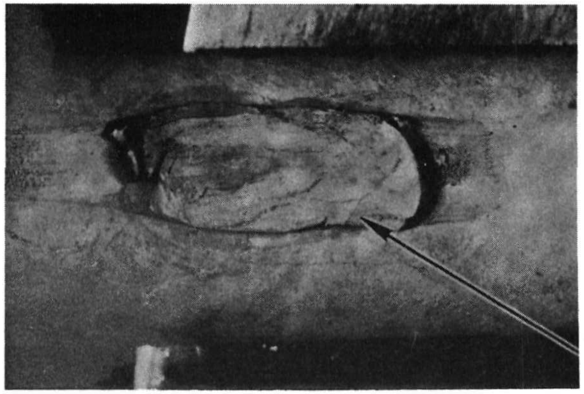


C EMBEDDED FOREIGN MATERIAL

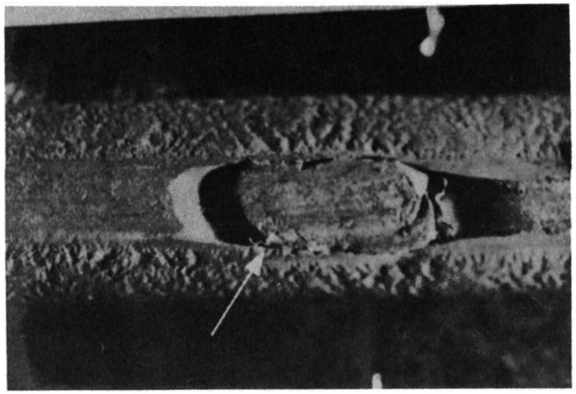


D TWIN LAPS IN OUTER SURFACE OF TUBING

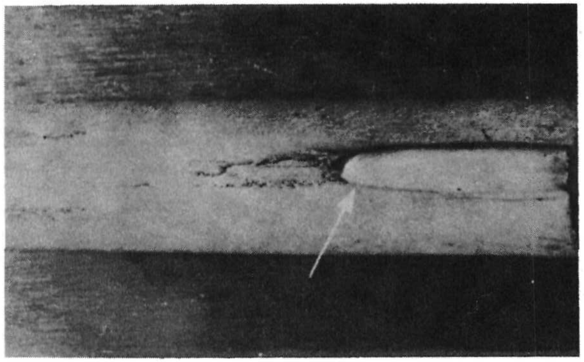
FIGURE II-23. HYDRAULIC TUBING DISCONTINUITY



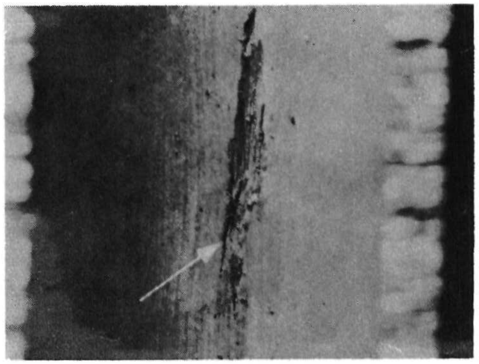
A EMBEDDED SLUG SHOWING DEEP GOUGE MARKS



B SLUG BROKEN LOOSE FROM TUBING WALL

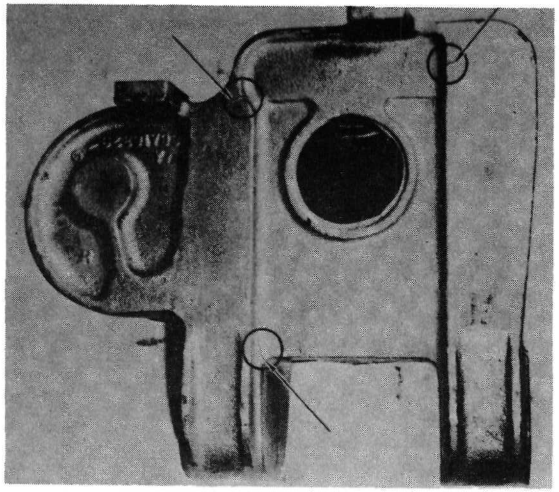


C ANOTHER TYPE OF EMBEDDED SLUG

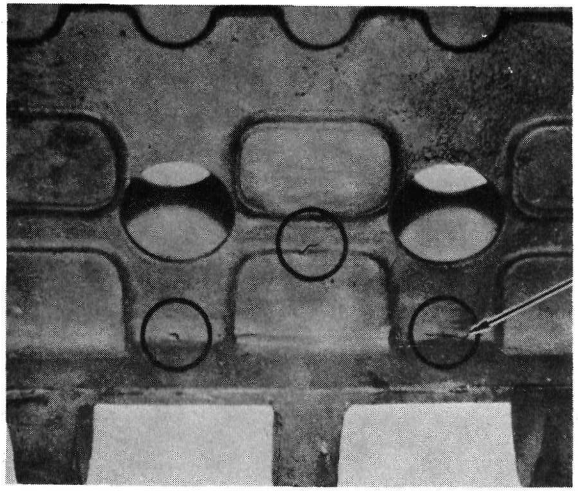


D GOUGE ON INNER SURFACE OF PIPE

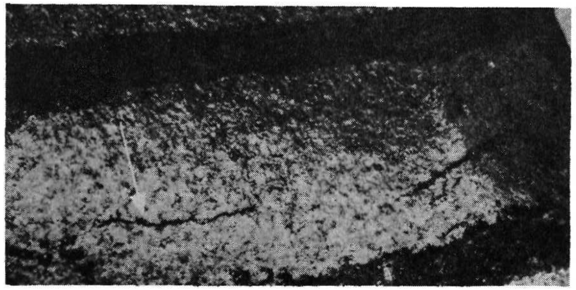
FIGURE II-24. MANDREL DRAG DISCONTINUITY



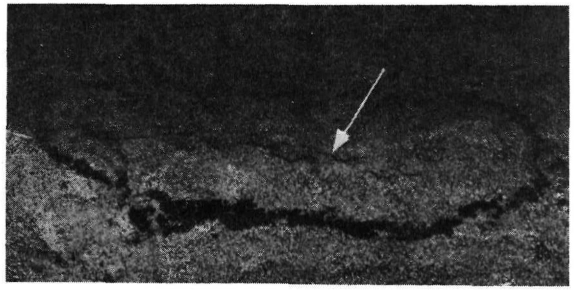
A TYPICAL HOT TEARS IN CASTING



B HOT TEARS IN FILLET OF CASTING

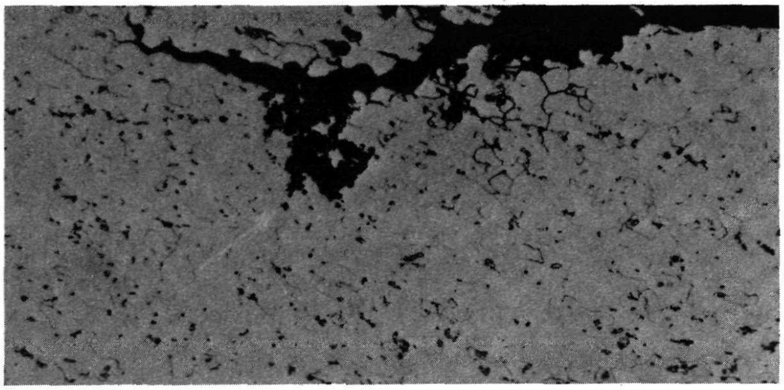


C CLOSE-UP OF HOT TEARS IN (A)

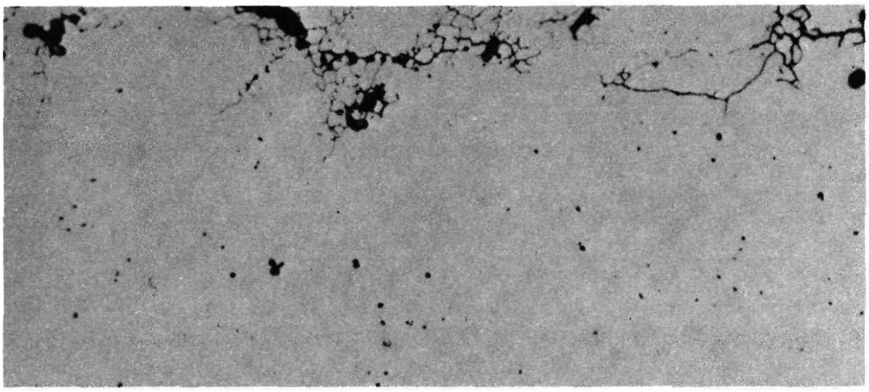


D CLOSE-UP OF HOT TEARS IN (B)

FIGURE II-25. HOT TEAR DISCONTINUITY



A MICROGRAPH OF INTERGRANULAR CORROSION SHOWING LIFTING OF SURFACE FROM SUBSURFACE CORROSION



B MICROGRAPH SHOWING NATURE OF INTERGRANULAR CORROSION. ONLY MINOR EVIDENCE OF CORROSION IS EVIDENT FROM SURFACE

FIGURE II-26. INTERGRANULAR CORROSION DISCONTINUITY method that is both technically sound and economical. The fixed or direct costs associated with each NDT process can be readily calculated and compared; intangible costs are much more difficult to estimate. Human safety must also be considered; it may outweigh other factors and narrow the selection.

To conduct a cost-effectiveness analysis, the objectives and criteria of inspection must be defined and the NDT procedures that can be used to attain these objectives must be enumerated. Then the relative costs associated with each alternative must be determined and compared to select the optimum approach.

To cite an example, the fixed costs of radiographic inspection are comprised of (1) prorated equipment costs, (2) operating costs (water, power, etc.), (3) film and film processing costs, (4) labor costs, and (5) overhead. The total of these costs is largely dependent on the number of exposures that must be made to satisfy the inspection requirements. To these costs must be added those associated with the actual radiographic procedure. Costs to set up a part for inspection vary widely, depending on its physical characteristics (size, weight, complexity, etc.) and the difficulty of radiographing the area of interest. Additional costs may be incurred if a manufacturing process must be interrupted to conduct the investigation.

A detailed estimation of the costs of nondestructive testing is beyond the scope of this report. However, some concept of the relative costs of the five major processes included in this report can be obtained by considering the information contained in Table II-5.

TABLE II-5. RELATIVE COSTS OF NONDESTRUCTIVE TESTING

	Cost Factor				
Method	Capital Equipment Costs	Set-Up Costs	Inspection Costs	Skill Requirements	Overall Costs
Penetrants	L	L	L	L	L
Magnetic Particles	M	M	L-M	M	M
Radiography	H	M-H	M-H	H	H
Ultrasonics	M	L-M	M	H	M
Eddy Currents	M	M	M	M	M

Note: H - High; M - Moderate; and L - Low

Although the costs of automating nondestructive testing methods may be significant, automation is frequently justified when the savings in time and labor are considered along with the inherent advantages associated with the use of standardized procedures. To cite an example, automated radiographic methods were developed to perform the 100 percent inspection of the welded joints in the Saturn S-1C booster that was required to insure the integrity of this structure.(6) The major components in the inspection system included (1) the X-ray tube and camera unit, (2) film handling equipment, (3) automatic film processor, and (4) a semi-automatic film-viewing console where the results of inspection were interpreted. With this equipment, the costs of exposing, processing, and reviewing film were reduced about 50 percent. Also, the total time that the work area had to be cleared for inspection was reduced, because of a reduction in the radiation hazard that permitted personnel to work within 10 feet of the inspection unit instead of the previously required 50 feet.

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CHAPTER III

PENETRANTS

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CHAPTER III

PENETRANTS

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CHAPTER III

PENETRANTS

Introduction

Liquid-penetrant inspection involves the use of colored or fluorescent dyes suspended in a liquid to detect fine surface-connected discontinuities. The penetrant is entrapped in discontinuities on the surface of the parts being inspected. After removing the excess, discontinuities are revealed by applying a developer that draws the entrapped penetrant to the surface. Liquid penetrants are relatively easy to use and involve very simple principles, but the inspection procedures must be controlled.

Scope

Penetrant inspection is widely used and is applicable to both metallic and non-metallic materials. However, it should not be used on porous materials or on materials that will be chemically attacked by the penetrant. Also, extreme care must be taken in some applications to prevent explosive reactions between residual inspection materials and the materials that will be used in service. Vessels designed to contain liquid oxygen, for example, must be either totally free of reactant residual penetrant or the materials involved must be inert.

Penetrants can only be used to locate surface defects. The defects must be sufficiently large to entrap the suspended dyes. Some shallow defects (e.g., fine grinding cracks) may not allow them to enter. The limiting dimensions of defects that can be detected vary widely, depending on the inspection techniques and materials. Cracks having a width of 0.01 μ have been detected in laboratory tests using fluorescent penetrant techniques.[(1)*] In practice, however, the minimum detectable crack width would ordinarily be larger than 0.01 μ. With colored dye penetrant, the minimum crack width resolved during this investigation was 50 μ. Another study indicated that cracks less than 0.25 inches in length cannot be detected reliably with penetrants under production conditions.[(2)]

Advantages and Disadvantages

The advantages of this inspection method are:

- Minimum equipment requirements
- Applicable to parts of all sizes
- Fast and economical
- Simple, once techniques have been mastered.

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* Superscript numbers refer to References at the end of this Chapter.

The disadvantages are:

- Limited to the detection of surface defects
- Defect depth cannot be determined
- Parts must be cleaned well before and after inspection.

Materials

Two primary materials are involved during inspection: (1) the penetrant, which enters defects that are open to the surface, and (2) the developer, which draws the entrapped penetrant to the surface and spreads it sufficiently to make discontinuities visible. In some systems, an emulsifier is used to render excess penetrant on the surface soluble without affecting that trapped in the defect.

Military specifications have divided penetrant systems into the seven basic groups listed in Table III-1. Each system has various areas of applicability, and these are outlined in Table III-2.

Penetrant Properties

The essential attributes of penetrant materials are their ability to: (1) wet the surface of the parts being inspected, and (2) penetrate surface-connected discontinuities. As indicated below, these materials are characterized by their penetrativeness, viscosity, visibility, body, volatility, wetting ability, and chemical reactivity.

(1) Penetrativeness. The most important property is high penetrativeness. It can be determined by applying the penetrant to a standard sample containing defects of various sizes and measuring the dimensions of the smallest defect entered.

(2) Viscosity. Viscosity is a measure of the ability of a penetrant to remain on the test surface. It is difficult to retain low-viscosity materials on surfaces being inspected long enough to permit defect penetration. However, process costs can be increased by using high-viscosity materials that cling to test surfaces.

(3) Visibility. Visibility is a measure of the ease with which defects can be detected. High visibility is generally obtained by providing high contrast between the penetrant and the developer. Visible dyes usually have a blood-red hue that is quite visible on the typically-white developer background. The brilliance of fluorescent dyes determines their visibility; brilliance is a measure of the intensity of light emitted under standard ultraviolet illumination conditions.

(4) Body and Volatility. Body determines the ability of a liquid to hold the dye (colored or fluorescent) in uniform suspension. If volatility is too high, the penetrant will evaporate before adequate defect penetration has been obtained. With low flash-point materials, volatility is a safety consideration. Materials

TABLE III-1. CLASSIFICATION OF PENETRANT MATERIAL SYSTEMS[(a)]

Group	Description
I	Consisting of a solvent-removable visible dye penetrant, a penetrant remover (solvent), and a dry or wet (aqueous or nonaqueous) developer.
II	Consisting of a postemulsifiable visible dye penetrant, an emulsifier, and a dry or wet (aqueous or nonaqueous) developer.
III	Consisting of a water-washable visible dye penetrant, and a dry or wet (aqueous or nonaqueous) developer.
IV	Consisting of a water-washable fluorescent penetrant, and a dry or wet (aqueous or nonaqueous) developer.
V	Consisting of a postemulsifiable fluorescent penetrant, an emulsifier, and a dry or wet (aqueous or nonaqueous) developer.
VI	Consisting of a high-sensitivity postemulsifiable fluorescent penetrant, an emulsifier, and a dry or wet (aqueous or nonaqueous) developer.
VII	Consisting of a solvent-removable fluorescent penetrant, a remover, and a nonaqueous wet developer.

(a) From MIL I-25135C(ASG) "Military Specification Inspection Materials, Penetrant".[(3)]

TABLE III-2. APPLICABILITY OF VARIOUS PENETRANT PROCESSES*

Inspection Problem	Preferred Process	Remarks
High production of small parts required	IV	Small parts handled in baskets
High production of large individual parts required	V,VI,II,III	Large forgings, extrusions, etc.
Highest sensitivity to fine defects required	VI	Brightest indication, most sensitivity
Shallow defects and scratches must be detected	II,V,VI	Depth of emulsification can be controlled
Parts have rough surfaces	IV	--
Threaded parts and keyways in parts to be inspected	III,IV	Other penetrants may lodge in corners
Parts have medium rough surfaces	IV,V,VI,VII	Choice depends upon production and sensitivity requirements
Spot testing of local areas only is desired	I,III	--
Portable equipment necessary	I,III	--
Water and electricity not available	I	--
Anodized parts, cracked after anodizing, to be inspected	I,III,VI,V,IV	Order of preference
Repeated application of process is required	II,III,V,VI	Five or six repeats should be the limit
Leak detection	III,IV	Penetrant only

* Adapted from Reference 4.

with low flash points are hazardous and may form explosive air-vapor mixtures over penetrant tanks; open flames in penetrant inspection area should be prohibited. The toxicity of penetrant materials should also be considered, because these materials may cause nausea if inhaled and may produce dermatitis upon prolonged contact with the skin.

(5) Wetting Ability. Good wetting ability is required so the penetrant will spread uniformly over the surfaces being inspected. Materials with poor wetting ability may leave parts of the surface uncoated and, therefore, uninspected.

(6) Reactivity. The materials used in the inspection process must not react with the materials of the part being inspected. For example, titanium alloys such as Ti-6Al-4V can develop stress-corrosion cracks in the presence of chloride or high-sulfur-bearing penetrants, developers, or solvents. The chemical compatibility of the inspection materials and the materials of construction must be established before the parts are inspected.

The specialized use of the components being inspected must also be considered. Thus, for example, care must be exercised in selecting penetrants and in inspecting components which will be in contact with liquid oxygen (LOX). Any residues of chemically-reactive materials used in penetrant inspection which remain in cracks, pores, or between faying surfaces are potential sources for catastrophic detonation if they come into contact with LOX. LOX-clean practice requires that the inspection materials be demonstrated to be nonreactive with LOX. Thus, the materials must be entirely removed from inspected surfaces by some means or any residues remaining must be chemically inert with LOX. There is no group classification for these LOX-compatible penetrant inspection materials. Rather, the materials are ordered specifically for this application and the manufacturer must demonstrate the nonreactivity of the system, as well as its sensitivity in detecting defects.

Developer Properties

The choice of a developer often determines the ultimate sensitivity of the penetrant inspection process. A good developer must: (1) draw penetrant materials from defects, and (2) spread these materials on the surface so that defect indications are easily visible. However, too much spreading results in a blurring of discontinuities and, in some instances, two discontinuities in close proximity may appear as one.

Emulsifier Properties

If used, an emulsifier must have suitable viscosity for each application. The emulsifier must blend with the penetrant rapidly enough to make the penetrant water-washable without unduly delaying the inspection process. However, it must not blend so rapidly as to permit emulsification of penetrant in a defect and loss of operator control. The emulsifier must also be tolerant of water and penetrant dilution--a normal occurrence--so that a small amount of dilution will not seriously affect results. In addition, the emulsifier should have a low flash point, low evaporation rates, and low toxicity.

Procedures

The following seven basic steps are involved in liquid penetrant inspection: (1) clean the surface to be inspected; (2) apply the penetrant; (3) allow a sufficient time for penetrant flow into surface discontinuities; (4) remove excess penetrant; (5) apply a developer to draw entrapped penetrant from discontinuities; (6) visually inspect and interpret test results; and (7) clean the part. Each of these steps is important and deserves separate consideration.

The surface of the object to be inspected must be clean and free from all contaminants. Solid contaminants such as carbon, engine varnish, paints, rust, scale, etc. should be removed by established methods such as vapor blasting or chemical dipping. Vapor degreasing is recommended for the removal of soluble contaminants. Methods such as sand blasting, shot blasting, cleaning with emery cloth, wire brushing, etc. are not recommended because they tend to close or cover discontinuities open to the surface. Water, oil, and grease may accumulate in surface discontinuities and prevent penetrant materials from entering; these contaminants must be removed or the test results will not be valid. Acids and chromates may diminish the fluorescence of some penetrant materials.

The appropriate penetrant must be carefully selected. This may be done with the aid of Table III-2, the advice of NDT experts, and manufacturers' information.

Penetrant may be applied by dipping, spraying, or brushing. Dipping is generally the preferred method if a large surface is to be inspected or many small parts are to be processed. Spraying or brushing is used for localized surface areas or where dipping is impractical. Penetrants which are commercially available in aerosol cans for spray application are ideal for field-inspection conditions.

The penetration or dwell time is determined by the penetrant system used, the material being inspected, the condition of the defect of interest, and the testing temperature. Dwell times range from 1 to 60 minutes; typical times are 5-30 minutes. For more specific information, reference should be made to manufacturers' data.

Methods used for removal of penetrant from the surface vary. Water-washable penetrants are removed by a coarse-pressure spray; the water temperature should be between 90 F and 100 F. Solvent-removable materials are removed by wiping the surface with a cloth dampened with the solvent. The penetrant should not be flushed from the surface with a solvent because it would also be flushed from discontinuities. The removal of postemulsifiable penetrants is a two-part process which consists of (1) applying an emulsifier by dipping, flowing or spraying, and (2) subsequently removing the penetrants with a coarse water spray. Figure III-1 illustrates the action of the emulsifier. Emulsification time (i.e., the time between the application of the emulsifier and the removal of the penetrant by the water spray) is critical. It must be long enough to permit the emulsifier to react with all of the surface penetrant, but must not be so long as to permit emulsification of the material entrapped in surface defects. Appropriate reaction times can enhance the detection of shallow or tight surface defects. Emulsification time is established by testing typical parts; it normally varies from a few seconds to about three minutes.

Following the removal of excess penetrant, a developer is applied to draw entrapped penetrant from discontinuities, and magnify the indication by spreading the penetrant on the surface. The choice of developer often determines the sensitivity of the entire process. Wet developers are applied to the part immediately following washing. They are often aqueous suspensions of the developer powder and are applied by dipping. Care must be exercised to maintain the proper suspension in the developer bath. When dry developers are used, the part must first be dried. These developers are applied by dusting or by burying the test object in the developer. Dusting is preferred, and a light dust film is preferred to a heavy coat. Most of the developers used with portable dye penetrant kits are the so-called solvent type. The developer powder is suspended in a liquid medium and is commonly applied by spraying from aerosol cans. A highly-volatile, suspending liquid is used as the medium to promote rapid drying. The development time must be long enough for the indications to reach their maximum intensity without excessive "bleeding" which reduces defect resolution. The time required varies according to the material and defect characteristics. A frequently used rule of thumb is to develop for a time equal to at least one-half of the penetration time. A development time of 15 minutes is typical.

In interpreting the test results, the inspector must be acquainted with the method of fabrication used to produce the part being inspected, must be familiar with the defects that are likely to produce harmful effects under service conditions, and must have the ability to read and interpret the indications. This knowledge and training enables the inspector to make an appropriate judgment as to the criticality of a given discontinuity.

As the final step in the process, the part must be cleaned. Regardless of the penetrant removal method used, the probability exists that some material will be left in surface discontinuities. This can be very hazardous under some conditions. As noted previously, such residues can be dangerous if the inspected surface is to be exposed to a liquid oxygen environment.(5) Therefore, one must choose a penetrant system whose characteristics are compatible with future service requirements of the part being examined.

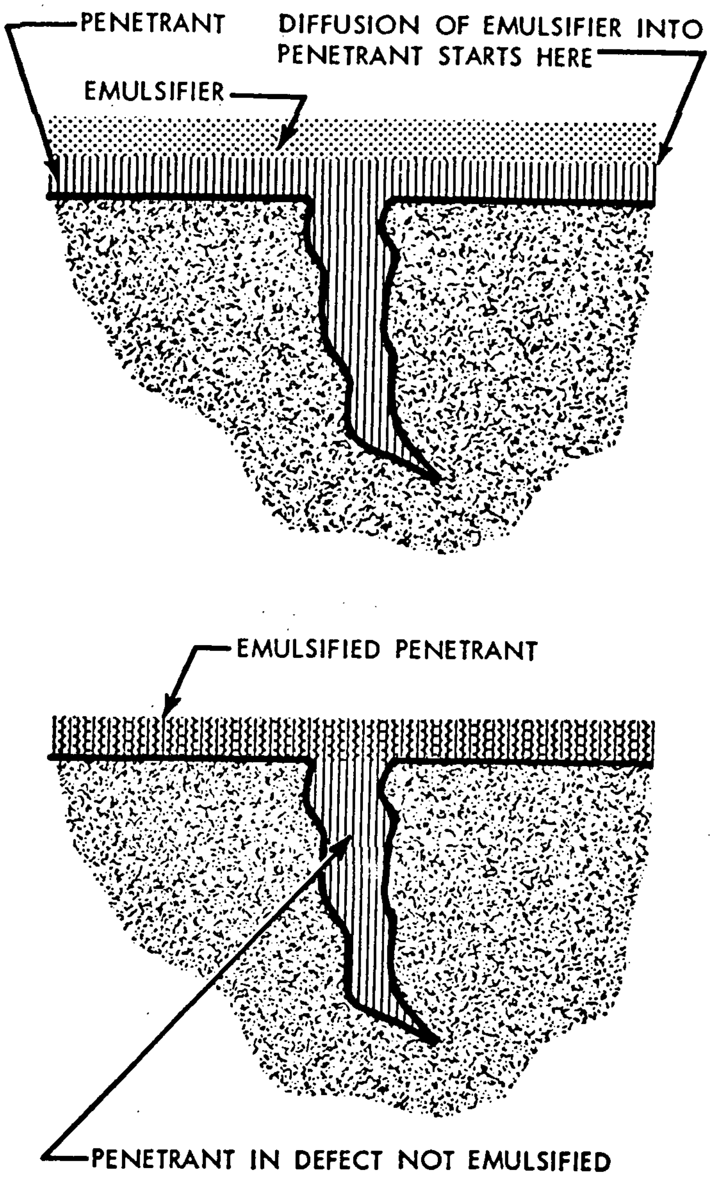

FIGURE III-1. ACTION OF EMULSIFIER IN POSTEMULSIFICATION PENETRANT SYSTEMS

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Developments

Although the basic penetrant test method is old, new techniques are continually being developed to increase the sensitivity or applicability of this inspection technique. For example, special techniques called "Wink-Zyglo" and Spin-Zyglo" have been developed to enhance detection of very fine cracks in turbine blades and other jet engine parts.(6) Using these procedures, the penetrant is applied while the part is dynamically stressed to open the crack. The part is cyclically stressed in Wink-Zyglo and is centrifugally stressed in Spin-Zyglo. One problem associated with these techniques, especially the former, is to assure that the part is not damaged by excessive stressing.

The hot-penetrant method has also been used to increase the inspection sensitivity. Before the penetrant is applied, the part to be inspected is heated to about 150 F and then allowed to cool. This procedure can increase sensitivity by lowering penetrant viscosity so that more penetrant enters the defect.

To inspect large aircraft parts, an electrostatic spray method for applying penetrant materials has been developed.(7) An electric field is used to accelerate and direct the penetrant to the test part. This technique assures more efficient use of these materials and permits uniform coating, even on very irregularly shaped parts.

Recently, a new plastic strippable developer was introduced. This developer is sprayed on the part as a liquid after removing the excess penetrant. After hardening, the developer forms a strippable transparent film which, when removed, serves as a permanent record of the defect indication. This developer has an additional advantage in that it inhibits bleeding of the penetrant after hardening and, thus, provides improved resolution of defect indications.

Work is currently in progress to develop a completely automatic penetrant test system for inspecting jet-engine blades.(8) Blades are prepared for inspection by applying and developing a fluorescent dye penetrant. The blades are then automatically scanned by TV-vidicon cameras, and the data is processed and evaluated on-line by a computer.

Applications

Penetrant testing is used extensively in all phases of hardware production to inspect:

- Incoming materials (e.g., sheet, plate, forgings, tubing, bar stock, castings)
- Manufactured parts at various stages of fabrication (e.g., machining, welding, heat treating, plating, forming)
- Finished parts, assemblies, and structures
- Parts during repair or maintenance operations.

In any situation involving the detection of surface defects, penetrant testing is one of the two preferred methods, the other being magnetic particle testing. Magnetic particle testing is generally preferred for magnetic materials, but penetrants are used on such materials also:

- To distinguish surface defects from defects just below the surface
- To economically inspect large numbers of small, complex-shaped parts
- To quickly inspect a part on the production line (e.g., for checking a small weld between welding passes).

Penetrant testing is widely used for inspecting:

- Castings for shrinkage cracks, micro-shrinkage surface porosity, cold shuts, surface sand inclusions, blow holes, and dross
- Forgings for laps, tears, bursts, flakes, laminations, age cracking, and pipe
- Rolled products for seams, laps, slivers, laminations, and pipe
- Welded and brazed joints for surface cracks, lack of fusion, and surface porosity.

Penetrant testing is commonly used in production after various manufacturing operations. For example, after cutting and machining a weld bevel on a plate, the edges might be inspected to assure that no delaminations have been exposed. After heat treating, complex-shaped parts might be inspected to assure the absence of quench cracks. After forming, such as in deep drawing, parts might be inspected to assure the absence of cracks in high strain areas.

Penetrant testing is also widely used as an in-process inspection method for welding. Partially completed, multiple-pass weld joints are inspected for surface cracks with this process; such tests are often supplemented by radiography. The initial or "root" pass of a weld is usually the most critical in terms of crack susceptibility, and it is commonly inspected with penetrants. In critical-service welds, or in cases where the completed joint cannot be radiographed, a penetrant test may be used to inspect each weld layer. When a weld is deposited from two sides in a thick plate, this method is frequently used to assure that adequate grinding of the back side of the initial weld pass has been accomplished before depositing the first pass from the second side.

Penetrants are often used for detecting leaks in welded tanks. Basically, the procedure consists of applying penetrant to one surface and observing seepage after the developer has been applied to the opposite surface. If a fluorescent penetrant is used, seepage can be observed with black light.

Occasionally, penetrants are used for the initial, overall inspection with ultrasonic, eddy current, and radiographic techniques being used to resolve questionable areas. This multiple NDT approach was used, for example, on the Saturn S-IC booster to inspect the aluminum plates used for the booster skin.[9]

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Glossary

black light - The term given to electromagnetic radiation having wavelengths between 300 and 3900 angstrom units. Typical units used in penetrant inspection provide an intensity of 100 to 150 foot-candles at 15 inches from the face of the filter and are used to excite the fluorescent materials in fluorescent penetrants.

body - Body is a term used to describe the ability of a penetrant vehicle to maintain an adequate suspension of visible or fluorescent dye material.

developer - Developers are materials which will draw or absorb penetrant materials from a surface discontinuity to a sufficient extent that the penetrant will be visible under natural, white or black light, as applicable. Developers may be either wet or dry. The term wet, or dry, as applied to developers, describes the room-temperature state of the developer's materials, as applied.

dye - The chemical component added to a penetrant vehicle to provide a characteristic color, usually deep blood red.

emulsifier - An emulsifier is an agent which will, when added or applied to an oil-like penetrant material, make the penetrant removable from surfaces by water rinsing.

emulsification time - Time allowed for the emulsifier to diffuse into the penetrant base material before rinsing with a coarse water spray.

flash point - Minimum temperature at which a flammable vapor mixture exists at the surface of a liquid.

fluorescence - The tendency for a given material to emit electromagnetic radiation when stimulated by radiation of a greater energy. As applied to penetrant inspection, fluorescence generally refers to the radiation of a bright yellow-green under the stimulus of ultraviolet radiation.

penetrant - A liquid containing either visible dye or fluorescent particles or constituents, which, when applied to the surface of a material, will tend to enter discontinuities which are open to the surface.

postemulsifier - An oil-like material which, after application to a surface, can be made water washable by application of an emulsifier.

penetration time - The time allowed for the penetrant to enter discontinuities open to the surface; also referred to as dwell time.

CHAPTER IV

MAGNETIC PARTICLES

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MAGNETIC PARTICLES

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CHAPTER IV

MAGNETIC PARTICLES

Introduction

Magnetic particle techniques are used to inspect ferromagnetic materials for surface or near-surface discontinuities. Magnetic fields are induced by passage of electric currents through or near the material. A discontinuity in the part being inspected causes distortion of the magnetic field due to differences in the permeability between the material (or void) in the defect and the ferromagnetic material surrounding it. If the discontinuity is at or near the surface of the part being inspected, the field distortion will cause leakage, creating apparent magnetic poles at the surface of the part. These poles attract ferromagnetic particles as shown in Figure IV-1. Thus, the collection of colored magnetic particles at the discontinuity reveals the discontinuity and contributes to evaluation of the integrity of the part.

Scope

Magnetic particle techniques cannot be used for the inspection of nonferromagnetic materials. Although applicable for detection of surface and near-surface discontinuities in any ferromagnetic material, the method is most suitable for inspecting materials with high permeabilities, such as low carbon steels. For alloy steels, the applicability of this technique depends on the heat treatment as well as the composition of the material to be tested. If uncertain, it is best to determine the applicability of this method with a sample of the material that contains a crack.

Advantages and Disadvantages

Advantages of the magnetic particle inspection method are as follows:

- Rapid, simple, and reliable for finding surface or near-surface cracks in ferromagnetic materials.
- No limitation on the size or shape of the part being tested.
- Indications produced directly on the object being tested; no auxiliary readout devices required.
- Relatively low operator skill required; techniques can be learned easily without lengthy or highly technical instruction.
- Capable of detecting discontinuities which are filled with nonpermeable foreign materials; thus, may be used even if the part has a thin coating of paint or other nonmagnetic material.
- Easily adapted to production line usage.
- Relatively inexpensive.

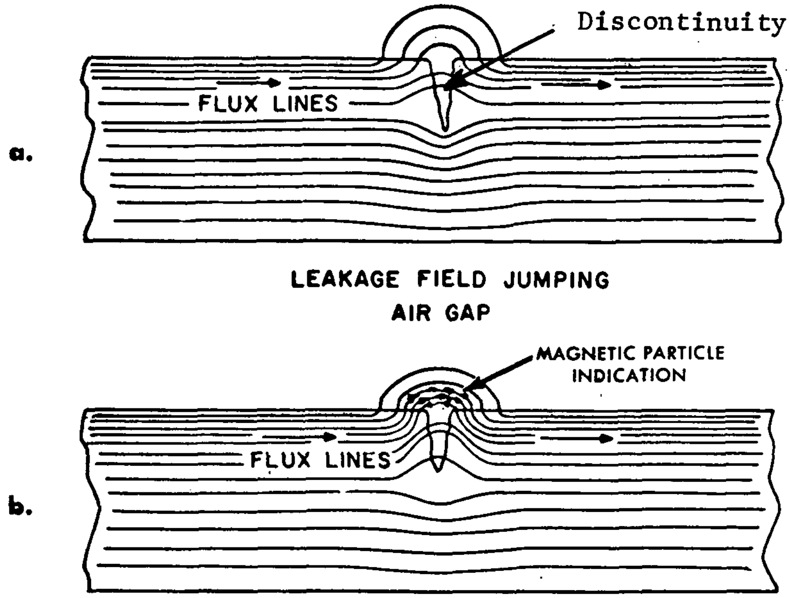


FIGURE IV-1. SCHEMATIC REPRESENTATION OF THE BASIC PRINCIPLE OF MAGNETIC PARTICLE INSPECTION

Magnetic particle inspection is subject to the following limitations:

- Applicable only to ferromagnetic materials.
- Only partially effective in locating subsurface discontinuities; as with most methods, sensitivity is dependent on defect orientation. The magnetic field must be in a direction perpendicular to the major axis of the discontinuity.
- Excessively high currents may be required for inspecting large or heavy sections; care necessary to avoid local heating and/or burning of highly finished surfaces.
- Demagnetization, following inspection, usually is necessary.

Materials

The only materials required for inspection are the magnetic particles themselves. Two methods (wet and dry) are used to distribute the magnetic particles over the surface of the test specimen. With the wet method, the particles are suspended in a liquid vehicle; with the dry method, the particles are borne by air.

The particles are selected magnetic materials with colored pigments or fluorescent materials added to improve visibility against the material background. With the wet method, either oil or water may be used; however, the proper type magnetic particles for the bath must be used in either case. Although the exact composition may vary, iron oxides are generally used as a base for the wet method. As discussed below, the properties which determine the usefulness of magnetic powder materials are: size, shape, density, permeability, coercive force, and visibility.

(1) Size

The size of the magnetic particle determines the type of defect that it may readily detect. Finer particles are most readily attracted to and held by weak magnetic fields. However, if a particle is too fine, it may be attracted by weak fields which are simply due to poor surface finish. Larger particle sizes are less mobile and are not attracted by very weak fields. A reasonable compromise in particle size must be made.

In general, the particles used for the dry method are coarser and, therefore, are more useful in inspecting parts with rougher surface finishes. Particles used for the wet method are generally finer to prevent excessive settling and are, therefore, better for finding very fine defects.

(2) Shape

Rod-shaped particles provide maximum sensitivity because it is easier to create strong poles in them. However, rod-like particles tend to "felt" together in a container and are very difficult to dispense with an air stream. Therefore, for the dry method, a mixture of globular and rod-shaped particles is generally used to provide the best combination of flowability and sensitivity. For the wet method, however, rod-like particles may be used exclusively.

(3) Density

The specific gravity of magnetic particles varies between five and eight. Since such high-density particles tend to settle in a liquid suspension, their density is decreased by compounding or coating them with a pigment having lower density. Low-density particles are also preferred for dry method inspection.

(4) Permeability

Theoretically, magnetic particles should have high permeability so that they will be readily drawn to the weak leakage fields around a defect. However, permeability is generally not the predominant factor in determining the effectiveness of particles. Materials with low permeability often take precedence because of better density, shape, and size properties.

(5) Coercive Force

Generally, low coercive force and low retentivity are desirable properties for magnetic particles. If these values are too high, the particles will become magnetized during production or during the first use. As a result, they will tend to stick to the test item where they first touch it and mobility will be decreased.

(6) Visibility

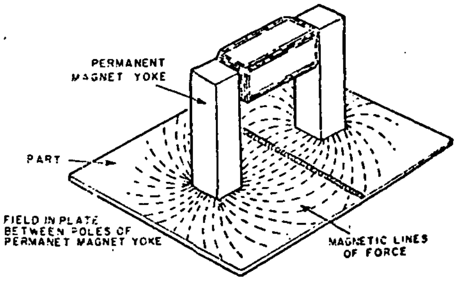
Visibility and contrast are extremely important properties of magnetic particles. In some cases, naturally occurring magnetic powders (e.g., red and black iron oxides) have colors that provide enough contrast so that indications can be easily seen against the background color of the test part. Pigments, either colored or fluorescent, are often added to magnetic particles to enhance their visibility.

The selection of any material for magnetic particle testing is based on the most appropriate compromise of all the foregoing properties for a particular application. A large variety of materials are available for both the dry and wet methods.

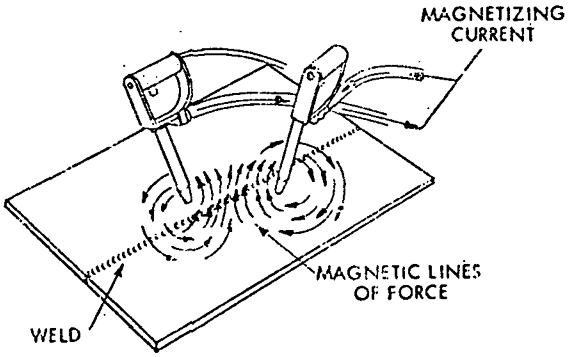
Equipment

A suitable source for inducing a magnetic field in the test part is required for magnetic particle testing. In the simplest case, this may be only a hand-held magnet called a yoke. Usually, electromagnetic induction techniques requiring a current generator are used. Auxiliary equipment may include particle dispensing equipment, materials handling systems, and black lights. There are many types of current generators used in magnetic particle inspection, and they vary in portability, current wave form, and method of producing a magnetic field.

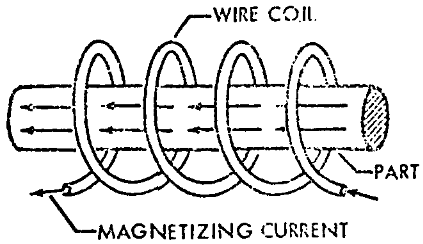
Three types of portable magnetization equipment that are suitable for field use are: (1) hand-held yoke, (2) prods, and (3) cable system. Inspection techniques are illustrated in Figure IV-2. Yoke and prod techniques may be used for the inspection of larger areas than can be inspected using a cable system. Small portable power supplies mounted on hand trucks and medium wheel-mounted units are available for field use with any of these techniques.



A. Yoke Magnetization[a]



B. Prod Magnetization[b]



C. Wrapped Coil Magnetization[b]

FIGURE IV-2. SCHEMATIC REPRESENTATION OF A. YOKE, B. PROD, AND C. WRAPPED COIL MAGNETIZATION TECHNIQUES

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Stationary equipment is designed for use with the wet method and may provide either A-C or D-C magnetization current (current selection is discussed on page IV-9). The part is magnetized by passing current through a stationary coil surrounding the part, or by passing the current through the part itself via contact plates as shown in Figure IV-3. A pumping system is usually used for dispensing wet magnetic materials with an agitation system keeping the magnetic particles in suspension. In some of the more sophisticated equipment, swinging field magnetization is provided. With this technique, an A-C current is used and half the cycle is passed through the encircling coil while the other half is passed through the part via contact plates. This permits the detection of discontinuities in both circumferential and longitudinal orientations.

Semiautomatic and automatic equipment has been constructed for some applications, such as the inspection of billets, in which the entire process is automated for production-line usage. This equipment is tailored to meet individual needs.

Procedures

There are seven basic steps in magnetic particle inspection:

(1) Selection of the method of magnetization.

(2) Selection of the appropriate current amplitude and wave form.

(3) Selection of particle type.

(4) Preparation of the part to be tested.

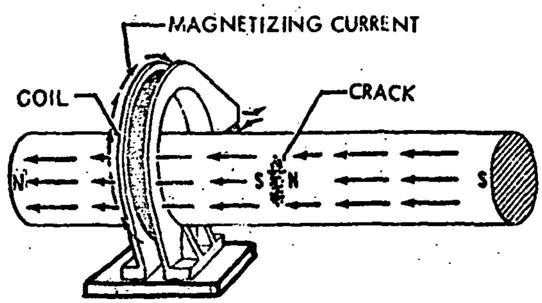
(5) Execution of the test.

(6) Interpretation of the test results.

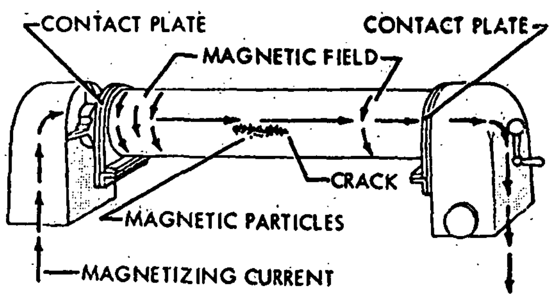
(7) Demagnetization and cleaning of the part after inspection.

All dirt, grease, oil, rust, and loose scale should be removed from the surface. In the case of wet inspection, the reusable liquid vehicle for the magnetic particles may become contaminated by the dirt, grease, oil, or rust that may be washed from the surface. Rust and scale may also provide lodging places for magnetic particles, and false indications may be produced as a result. For dry magnetic particle inspection, the same requirements hold and, in addition, the part must be dry. Any liquid on the surface, such as oil, grease, or water, will cause adherence of the dry particles to the surface and prevent their migration to a defect site.

The method of magnetization is chosen on the basis of the characteristics of the part and the type of defect to be detected. The magnetic field must be perpendicular to its major axis. Figure IV-4 illustrates the type of defects detectable in a cylindrical object using longitudinal and circular magnetization. If the object to be inspected has a nonconductive coating, it may not be possible to pass current through the part, and alternate methods of achieving the required field orientation using a noncontact method may have to be considered. If adequate alternate methods are not available, coatings may have to be removed. If a part is too large for available stationary equipment, it may be necessary to use prod, wrapped



A. Stationary Coil



B. Magnetization via Contact Plates

FIGURE IV-3. CONVENTIONAL MEANS OF MAGNETIZATION EMPLOYED IN STATIONARY MAGNETIC PARTICLE TEST EQUIPMENT

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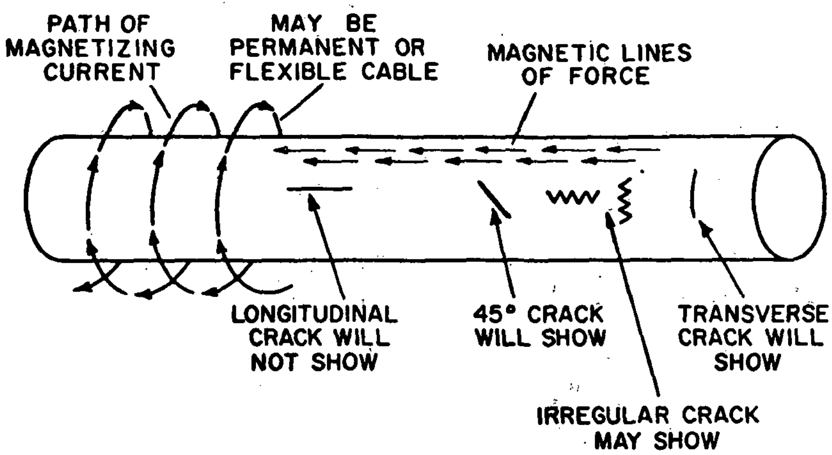
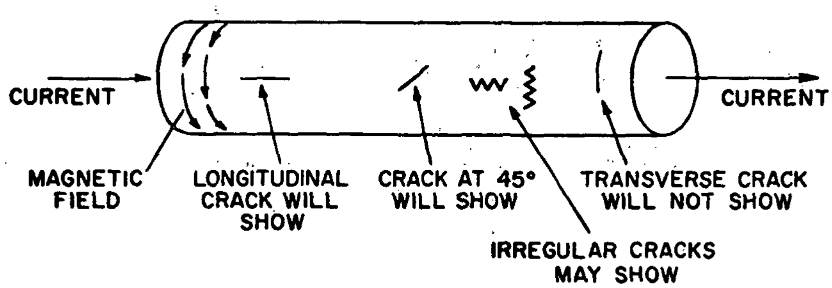


A. Longitudinal Magnetization



B. Circular Magnetization

FIGURE IV-4. DETECTABILITY OF VARIOUSLY ORIENTED DEFECTS FOR LONGITUDINAL AND CIRCULAR MAGNETIZATION OF A BAR coil, or yoke methods of magnetization. Actually, the method of magnetization is chosen to be compatible with application and has little effect on test sensitivity.

The choice of current amplitude and wave form has a significant effect on the sensitivity of magnetic particle inspection. There are three basic current wave forms: (1) direct current, (2) half-wave rectified alternating current, and (3) alternating current. Direct current, probably the most widely used, is usually rectified three-phase alternating current. Direct current provides the deepest penetration into the part being inspected, and, therefore, is most useful for the detection of deep-lying subsurface discontinuities. Half-wave rectified alternating current imparts increased mobility to the magnetic particles; high particle mobility aids in the formation of defect indications, particularly when dry particle inspection is used. Because of the "skin effect", alternating current magnetization produces fields which are most concentrated near the surface; it is best suited for the detection of fine surface cracks, particularly tight fatigue cracks.

Current amplitude determines the flux density. If the flux density is too low, important defects may go undetected. However, if the flux density is too high, the magnetic particles will adhere to the surface of the part and will not have sufficient mobility to migrate to the defect location. As a rule of thumb, 400 to 800 amperes per linear inch of section thickness are required for circular magnetization. For longitudinal magnetization, the appropriate current amplitude depends on the diameter-to-length ratio of the part and may be estimated with the formula:

$$I = \frac{45{,}000D}{LN}$$

where

I = current in amperes

D = part diameter

L = part length, and

N = number of turns in the coil.

In practice, current amplitude must be determined experimentally.

Selection of wet or dry methods is highly dependent on the material condition and the nature of the suspected defect. The wet method is best suited for use on smooth surfaces and for the detection of fine surface defects, such as fatigue cracks. The dry method is best for use on rough surfaces, and this method is usually preferred for field inspection; however, aerosol dispensers are available for wet inspection in the field.

Magnetic particle inspection may be done using either: (1) the continuous method, in which the magnetic particles are applied during the application of the magnetizing current, or (2) the residual method, in which the magnetic particles are applied to the part after the current pulse has been completed. The residual method is less sensitive and may be used successfully only with materials having very high retentivity. Sometimes, the residual method is used to confirm a suspected subsurface discontinuity which was discovered using the continuous method. In such a case, the indication formed by the continuous method is removed and the magnetic particles are reapplied. If the indication returns, this is usually a sign that the discontinuity is at the surface. If the indication does not return, the discontinuity probably is beneath the surface.

Satisfactory interpretation of test results requires that the inspector have knowledge of the part being inspected, the service requirements, and the accept/reject criteria. Not all discontinuities are cause for parts rejection. The inspector must be aware of the basis for a rejectable discontinuity so that he may sort out defective parts from those that are usable.

Following the completion of magnetic particle testing, it is usually important that all residual fields be removed, since they may impair the future serviceability or fabricability of a part. For example, ball bearings will not operate properly if they have been magnetized. Residual magnetic fields also interfere with some fabrication processes, such as arc welding. Demagnetization is accomplished by applying an alternating field with sufficient initial strength to overcome the initial coercive force and then gradually reducing the magnitude of the field. This takes the part through a series of decreasing hysteresis loops.

New Developments

In recent years many new magnetic particle inspection techniques have been developed. One such technique involves the use of magnetic tape for retaining inspection records. Rather than using magnetic particles directly, the magnetic tape can be laid on the surface of a part and the part then can be magnetized. The resultant leakage flux will be recorded on the magnetic tape in much the same way as magnetic tape records music. This tape may then be used as a replica and magnetic particles may be spread upon the tape to provide the same indications that would have been formed on the original part. This technique provides a means for permanently storing inspection results. The classification of discontinuity depth has been reported using this method.[(1)*]

Another recent development is the magnetic rubber inspection technique.[(2)] With this technique a silicone rubber suspension of finely divided magnetic material is used as the indicator. The material is catalyzed and applied to the part in a liquid form. The catalyst promotes the solidification of the silicone rubber. A magnetic field is applied before solidification, and this causes the suspended particles to migrate to the location of any leakage flux where the particles are entrapped by the solidifying rubber. The replica may then be removed and will show not only crack locations, but also a replica of the surface texture. The technique may be used for any magnetic particle inspection task, but it is particularly useful for inspecting inaccessible areas, such as threaded holes and parts whose shape or configuration prevents conventional particle inspection.

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* Superscript numbers refer to References shown at the end of this Chapter.

Another recently developed technique is the magnetic induction method in which a part is magnetized and scanned with a small coil.(3) If this coil interrupts any leakage field, an electrical signal will result and indicate the presence of a defect. This technique is currently being used for the inspection of helicopter blades.

Applications

In general, the applications for magnetic particle testing are the same as those previously discussed for dye penetrant testing; however, the test parts must be ferromagnetic. Magnetic particle testing is used for:

- Inspecting incoming materials
- In-process inspection
- Final inspection
- Maintenance inspection.

As with penetrant testing, this technique may be used to inspect castings, forgings, rolled products, and welded joints.

One application in the space industry involves the examination of welds in solid propellant rocket motor cases.(4) In one instance, the wet method was used (the liquid oil-base suspension was sprayed from an air gun) with continuous magnetization; black light sources were used to view the fluorescent indications. One method of magnetization for the rocket motor case consisted of a one-turn coil which closely conformed to the inside chamber of the motor case with the return path in close proximity to the outside surface of the container. This provided a strong circular magnetic field. Longitudinal magnetization was provided by a yoke-like fixture. Both are illustrated in Figure IV-5.

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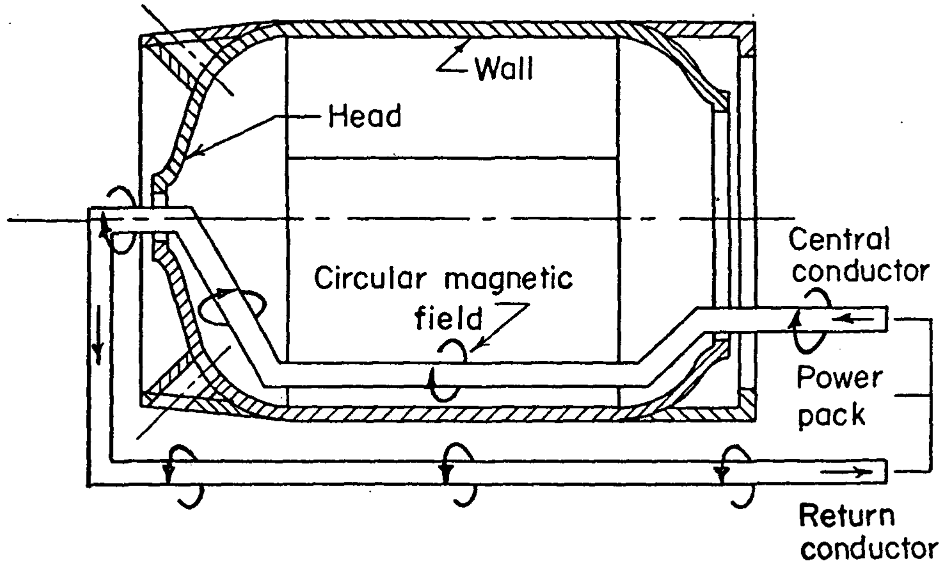
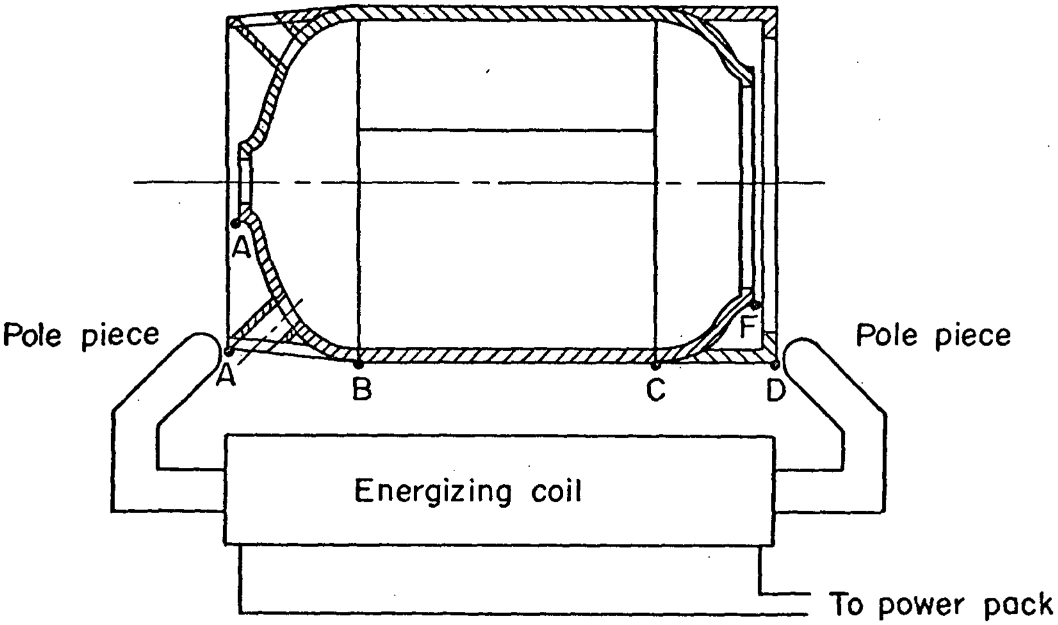
(2) Kaarlela, W. T., et al., "Magnetic Rubber Inspection - Descriptive Report", General Dynamics Report FZM-12-10769, Revised (June, 1970), Fort Worth, Texas.

(3) Whealy, R. D., and Intrieri, A., "Nondestructive Inspection of an Advanced Geometry Composite Blade", Paper Presented at Conference on NDT Plastic/Composite Structures, Dayton, Ohio (March, 1969).

(4) Pasley, R. L., and Seale, C. L., "Nondestructive Testing of Solid Propellant Rocket Motors", DMIC Memorandum 1959, Defense Metals Information Center, Columbus, Ohio (October, 1962).



A. Circular Magnetization Technique



B. Longitudinal Magnetization Technique

FIGURE IV-5. TECHNIQUES FOR MAGNETIC PARTICLE INSPECTION OF ROCKET MOTOR CASE BY CIRCULAR AND LONGITUDINAL MAGNETIZATION

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Betz, C. E., Principles of Magnetic Particle Testing, Magnaflux Corporation, Chicago, Illinois (1967).

"Magnetic Particle Testing: Classroom Training Manual", NASA CR-61227, National Aeronautics and Space Administration, Huntsville, Alabama (January 1, 1967).

Glossary

black light - The term applied to electromagnetic ultraviolet radiation having wave lengths between 3300 and 3900 angstrom units.

circular magnetization - Circular magnetization involves the production of a magnetic field in a part such that the magnetic lines of force are completely contained within the part.

coercive force - Coercive force is the value of negative magnetizing force necessary to bring the flux density back to zero after saturation. Coercive force determines the reverse magnetizing force necessary to demagnetize a part.

continuous method - The continuous method of magnetic particle inspection consists of applying or otherwise making available on the surface of the part an indicator while the part is being magnetized.

discontinuity - Any deviation from the normal homogeneous distribution of material in a part. A discontinuity does not necessarily constitute a defect. A discontinuity may be considered a defect only when it adversely affects the performance of a part in its projected service environment.

ferromagnetic material - A material in which the elementary magnets (electron spins) in substructures, referred to as domains, become aligned under the influence of a magnetic field. In general, a ferromagnetic material is strongly, rather than weakly, attracted by a magnet.

fluorescence - Term used to describe the effect produced by certain chemical products which emit visible radiation during activation by black light.

flux - The normal component of magnetic field through an element of area multiplied by the total area of the surface.

hysteresis loop - The hysteresis loop of a material is a curve showing the flux density, B, plotted as a function of magnetizing force, H, as the magnetizing force is increased to the saturation point in both the positive, negative, and positive direction sequentially. The curve forms a characteristic open, S-shaped loop. Intercepts of the loop with the B-H axis and the points of maximum and minimum magnetizing force define important magnetic characteristics of the material.

Glossary
(Continued)

<u>induction</u> - Magnetic induction is the magnetism produced in a ferromagnetic body by some outside magnetizing force.

<u>leakage flux</u> - That portion of the magnetic field which emerges at the surface of a part and penetrates the surrounding environment.

<u>longitudinal magnetization</u> - Longitudinal magnetization involves the production of a magnetic field in a part such that the magnetic lines of force are parallel to the axis of the part being tested. Longitudinal magnetization is generally induced through use of an encircling coil and is effective for locating discontinuities lying transverse to the axis of the part.

<u>magnetizing current</u> - The current passed through the part, encircling coil, yoke, or other electromagnetic device that gives rise to the required magnetic field.

<u>magnetizing force</u> - Magnetizing force, measured in oersteds, is a measure of the force acting on a unit pole. In magnetic particle testing, this is a measure of the force tending to draw particles to a defect.

<u>permeability</u> - A property of a material which characterizes the ease with which a magnetic field or flux can be established in a magnetic circuit. Permeability is defined as the ratio of flux density to magnetizing force.

<u>pole</u> - The point at which magnetic lines of force emerge from or enter into a ferromagnetic material.

<u>prod</u> - A special electrode used to introduce a current into a part to produce a magnetic field.

<u>reluctance</u> - Reluctance characterizes the opposition of a medium to the presence of a magnetic field. It is analogous to resistance in an electric circuit.

<u>residual method</u> - In the residual method of examination, the magnetic substance is applied to the piece after it has been magnetized and the magnetizing current is off.

CHAPTER V

RADIOGRAPHY

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CHAPTER V

RADIOGRAPHY

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CHAPTER V

RADIOGRAPHY

Introduction

Radiography involves the use of radiation to obtain information about the internal structure of a part or assembly. Radiation energy is attenuated as a function of material thickness, density, and chemical composition. Since many defect conditions represent an apparent change in one or more of these factors, they cause a predictable change in transmitted or reflected radiation. For example, porosity in a weld represents an apparent decrease in material thickness, and permits the transmission of more radiation than a homogeneous weld.

Radiography usually involves the use of a film to detect and record an image of the test result. Other imaging techniques are also available.

X-ray or gamma-ray sources are usually used in radiography, but other types of penetrating radiation such as alpha, beta and neutron particles are used also. Although this chapter will emphasize standard radiographic methods using X-ray or gamma-ray sources, a brief section has been included on other penetrating radiation techniques.

Scope

Radiography, one of the most widely used nondestructive testing methods, is applicable to almost all material and material configurations subject to the following restrictions:

- Homogeneity: For maximum effectiveness, the bulk of the material being tested must be homogeneous with respect to the transmission of radiation. Otherwise, a defect might be obscured by naturally occurring "noise".
- Defect orientation: To be discernible, a discontinuity must present a detectable difference in thickness (i.e., radiographic contrast) in the direction parallel to the propagated radiation. As a result, radiographic processes have a limited capability of detecting laminations in flat plate.

Radiographic techniques are generally capable of detecting discontinuities which change the apparent section thickness by 1 to 2 percent.

Advantages and Disadvantages

Radiography has the following advantages:

- Permanent Record: A permanent film record showing defects in relation to significant features of the part is obtained.

- Separately Sensitive to Multiple Defects: The exact nature of defects can be more readily determined from visual images than from chart records or electrical output indications. Defects in a weld (cracks, porosity, and lack of penetration) are separately imaged and recognizable. Radiography is the best and, perhaps, only reliable method for determining the extent of internal porosity in a part.

The major disadvantages of radiography are:

- Access: Access to both sides of the part is required.
- Defect Orientation: Defects must represent a significant effective difference in thickness along the beam path. Thus, radiography is not a reliable method for detecting small tight cracks or randomly-oriented cracks (e.g., cracks in welds).
- Cost: Radiography requires a relatively high investment in equipment and facilities. Films and chemicals add significantly to operating costs.

X-Ray and Gamma Ray Properties

X-rays and gamma rays are electromagnetic radiations of very short wavelength. They are similar in characteristics and properties, but are produced in different ways. X-rays are the result of extranuclear events associated with the electron orbits of an atom or molecule; they are usually produced by high-energy electrons striking a metal target. Gamma rays originate from nuclear transformation; the sources of gamma rays are called isotopes. X-rays generally exhibit white or continuous energy spectra, while gamma rays are usually monochromatic. Radiation energy is a measure of penetrating power. Since gamma rays possess more energy than X-rays, they will penetrate thicker sections. Radiation intensity is a measure of the quantity of energy produced. X-rays and gamma rays are reflected, refracted, and absorbed as they propagate through a material.

Equipment

X-Ray

X-ray equipment range from small, hand portable units with maximum energy outputs of 100-150 Kev to large units weighing several tons that produce radiation energies on the order of 25 million electron volts. The capabilities of various X-ray units are listed in Table V-1. In addition to the wide variability in output, X-ray units also differ in current wave forms, beam patterns, and basic design.

The basic controls for X-ray units include: (1) voltage selector, (2) current selector, and (3) timer. Maximum radiation (and penetrating power) is determined by the accelerating voltage. It is selected to produce the required contrast while providing adequate penetration. The current level

TABLE V-1. TYPICAL X-RAY MACHINES AND THEIR APPLICATIONS

Maximum Voltage (Kv)	Screens	Applications and Approximate Thickness Limits
50	None	Thin sections of most metals; moderate thickness of graphite and beryllium; small electronic components; wood, plastics, etc.
150	None or lead foil	5-inch aluminum or equivalent. 1-inch steel or equivalent.
	Fluorescent	1½-inch steel or equivalent.
250	Lead foil	2-inch steel or equivalent.
	Fluorescent	3-inch steel or equivalent.
400	Lead foil	3-inch steel or equivalent.
	Fluorescent	4-inch steel or equivalent.
1000	Lead foil	5-inch steel or equivalent.
	Fluorescent	8-inch steel or equivalent.
2000	Lead foil	8-inch steel or equivalent.
8 to 25 MeV	Lead foil	16-inch steel or equivalent.

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determines the quantity or intensity of radiation and is chosen to permit film exposure in a reasonable length of time. The timer permits automatic control of exposure and equipment functions.

Gamma Ray

Gamma-ray equipment includes devices to manipulate the radiation source while providing for personnel safety. The basic components of a gamma camera are (1) a means for transporting the radiation source, (2) a shield to reduce the radiation output of the isotope to a level safe for personnel in the area, (3) a means for unshielding the isotope for the test, and (4) a locking device to prevent unauthorized use of the source. A typical gamma camera is illustrated in Figure V-1. The characteristics of several typical sources used for gamma radiography are shown in Table V-2.

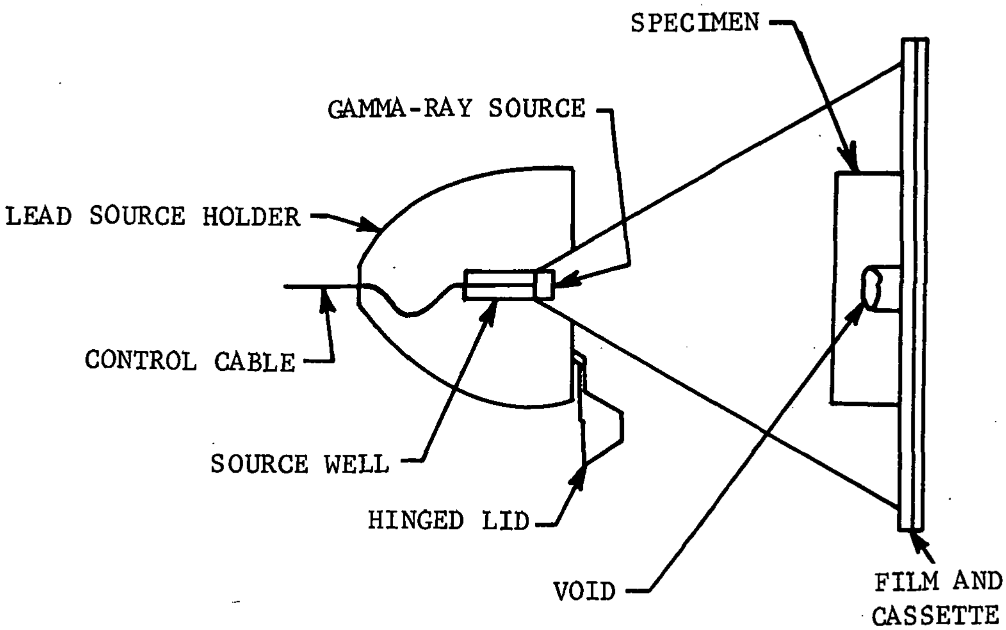

FIGURE V-1. TYPICAL GAMMA CAMERA AND SOURCE SHIELD[1]

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* Superscript numbers refer to References at the end of this Chapter.

TABLE V-2. TYPICAL GAMMA SOURCE CHARACTERISTICS(2)

Element	Co	Ir	Tm	Cs
Isotope	60	192	170	137
Half-life	5.3 yr.	75 days	130 days	33 yr.
Chemical form	Co	Ir	Tm_2O_3	CsCl
Density	8.9	22.4	4	3.5
Gammas M.e.v.	1.33, 1.17	0.31, 0.47, 0.60	0.084, 0.052	0.66
Abundance of γ's, γ/disint.	1.0, 1.0	1.47, 0.67, 0.27	0.03, 0.05	0.92
Betas, M.e.v.	0.31	0.6	1.0	0.5
R.h.m./curie	1.35	0.55	0.0030	0.37
Linear self-absorption coef.'s, cm.$^{-1}$				
Neutrons	3.0	33	1.5	
Gammas	0.22	5.1, 2.1, 1.4	22.0, 17.6	0.10
Ultimate specific activity, $(c/g)_{ult.}$	1,200	10,000	6,300	25
Practical specific activity, c/g	50	350	1,000	25
Practical curies/cc.	450	8,000	4,000	90
Practical r.h.m./cc.	600	4,400	10	33
For 50% γ self-abs., curies	200,000	3,000	2	500,000
For 25% γ self-abs., curies max.	10,000	150	0.1	25,000
Practical radiographic sources:				
Curies	20	50	50	75
R.h.m.	27	27	0.1	30
Approx. diam.	3 mm.	3 mm.	3 mm.	10 mm.
Lead pig diam.	13 in.	6 in.	2 in.	8 in.
Shield weight	500 lb.	50 lb.	2 lb.	120 lb.

Gamma sources are characterized by their energy and activity. The radiation energy which governs penetration is determined by the selection of the isotope. In contrast to X-ray sources, these sources of radiation are not variable; therefore, a specific source is used for a variety of material dimensions. The exposure time is adjusted to provide an adequate film density. Gamma sources are frequently used for field tests where X-ray equipment would be unwieldy. High-energy gamma sources, such as Cobalt 60, are also often used where the expense of high voltage X-ray equipment cannot be justified. The activity of a gamma source determines the intensity of the radiation and the time required for a given exposure. Gamma sources lose activity continuously. This loss is governed by the half life of an isotope, the time required to decay to half of the original activity level.

Standard Procedures

The best known and most widely used nondestructive testing procedure using penetrating radiation is X-radiography. The basic principles of this test are shown in Figure V-2. X-radiographic procedures are discussed below.

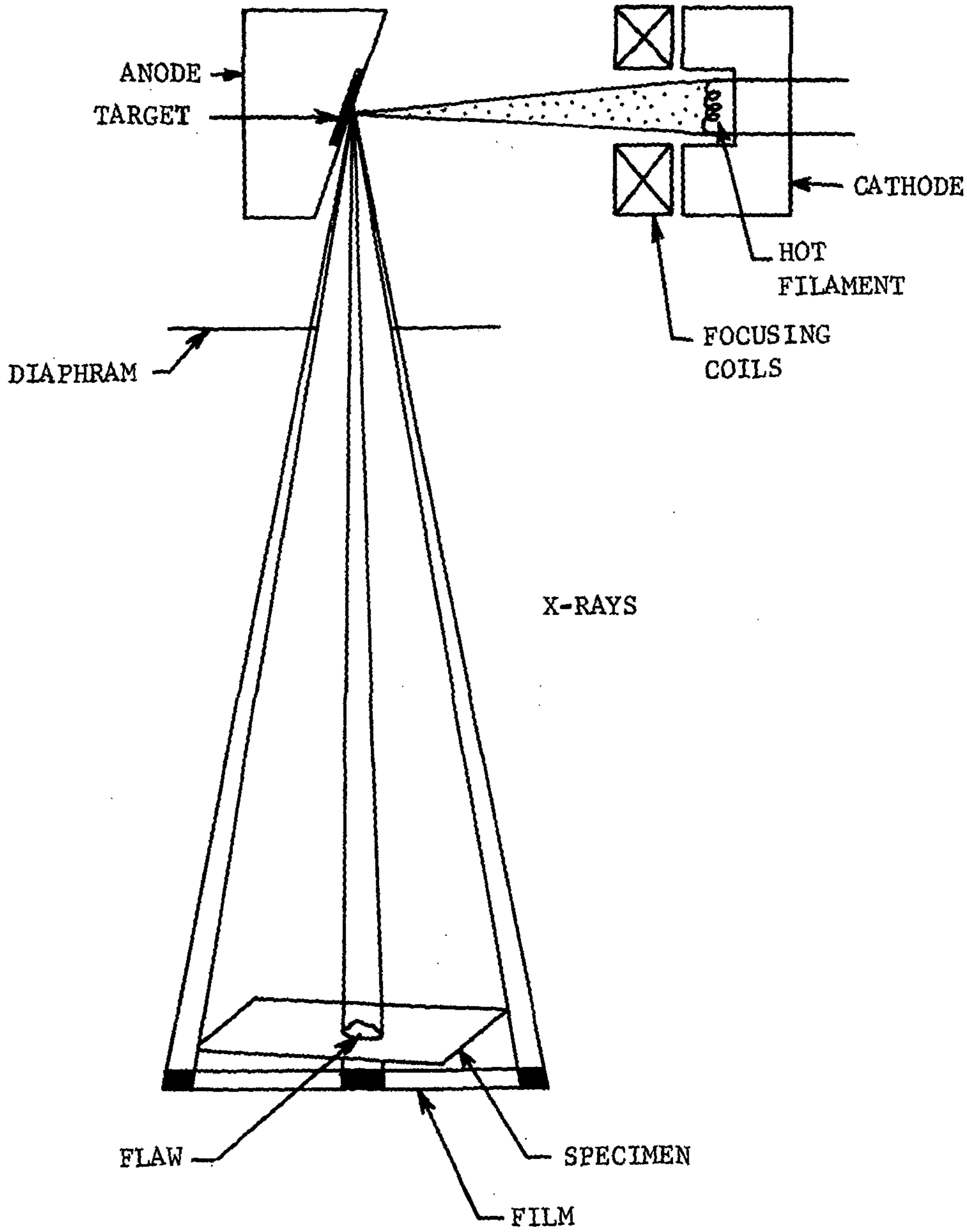

FIGURE V-2. BASIC PRINCIPLE OF RADIOGRAPHY

Exposure Setup and Part Orientation

The exposure setup determines the type and size of defect discernible. The defect must be so oriented that its dimension in the direction of radiation propagation is sufficient to result in a detectable difference in X-ray absorption. Since orientation is critical, a tight crack must be oriented within a few degrees of the direction of radiation propagation or it will not be detectable. X-ray inspection will not detect planar discontinuities such as laminations unless they are large and/or oriented parallel to the direction of radiation.

Marking of the test part is necessary to correlate the location of defect signatures in the radiograph with their position in the part. Marking is usually accomplished with lead letters. Penetrameters, typical designs of which are shown in Figure V-3, are used to measure the resolution obtained in the final radiograph. The penetrameter must be visible for a radiograph to be considered satisfactory. The penetrameter thickness is a known percentage of the part thickness, and its visibility is an indication of the sensitivity obtained. The penetrameter also contains a set of calibrated holes which are related to the penetrameter thickness and serve as a measure of the resolution obtained. Sensitivity, as determined by penetrameter visibility, is shown in Table V-3.

TABLE V-3. RADIOGRAPHIC QUALITY LEVELS[3]

Sensitivity[a]	Quality Levels	Penetrameter T as % of T_m	Perceptible Hole Diameter
0.7%	1-1T	1%	1T
1.0%	1-2T	1%	2T
1.4%	2-1T	2%	1T
2.0%	2-2T	2%	2T
2.8%	2-4T	2%	4T
4.0%	4-2T	4%	2T

(a) Standard 2% sensitivity requires that the technique image the penetrameter whose thickness (T) is 2% of the material thickness (T_m) and the 2T hole of the penetrameter. Other sensitivities are defined in a similar manner. For specimen thicknesses that are between penetrameter sizes, the smaller penetrameter must always be used.

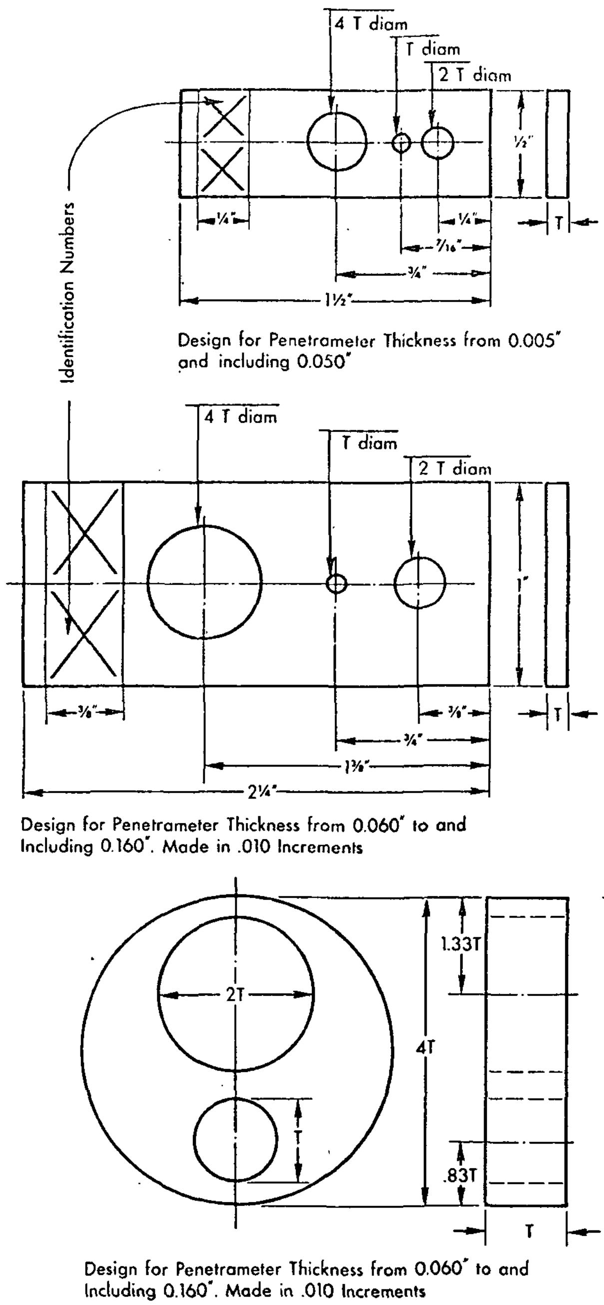

FIGURE V-3. X-RAY PENETRAMETER DESIGN SPECIFIED BY AMERICAN SOCIETY FOR TESTING AND MATERIALS, ASTM-E 142-68, METHODS FOR CONTROLLING QUALITY OF RADIOGRAPHIC TESTING(1)

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Test Conditions

The selection of test conditions includes the determination of the voltage, current, source-to-film distance, type of film, and the time of exposure. As noted previously, voltage is selected for the required penetration and contrast, while current is chosen to permit the exposure of a suitable radiograph in a reasonable time.

Source-to-film distance (SFD), the distance between the source of radiation and the plane of the film, determines the "geometrical unsharpness" and, therefore, the quality of the final image. Geometrical unsharpness (Figure V-4) occurs because the focal spot of an X-ray unit has finite dimensions. Since radiation intensity falls off with the inverse square of the distance, an increase in the SFD reduces the geometrical unsharpness, but decreases the radiation intensity. These two factors must be weighed against each other to select the appropriate SFD. Typical SFD values giving reasonable results are between three and four feet.

The three basic grades of film for industrial radiography are: coarse grain, fine grain, and extra fine grain. The fine and extra-fine grain film produce the highest contrast or sensitivity, but require relatively long exposure times in comparison with those required for coarse-grain films. A choice must be made between the allowable exposure time and the required sensitivity.

Exposure

The radiograph is exposed in accordance with established procedures. After exposure, the film is processed to produce a permanent record. Film must be handled carefully at all times to prevent the introduction of artifacts on the film. Artifacts are superficial indications (static marks, water spots, fog, etc.) that complicate the interpretation of the results.

Interpretation of Results

Interpretation is, perhaps, the most difficult step in the radiographic procedure. A radiograph is a two-dimensional representation of a three-dimensional object which must be interpreted to detect the existence and the seriousness of defects. Therefore, the interpreter must be familiar with the part being tested, must be aware of what constitutes a rejectable defect, and must be well trained in the interpretation of radiographic results. Even the best interpreter can make errors in judgment.

Special Techniques

In addition to the conventional X-ray and gamma ray techniques, there are several special techniques which are designed to meet specific objectives.

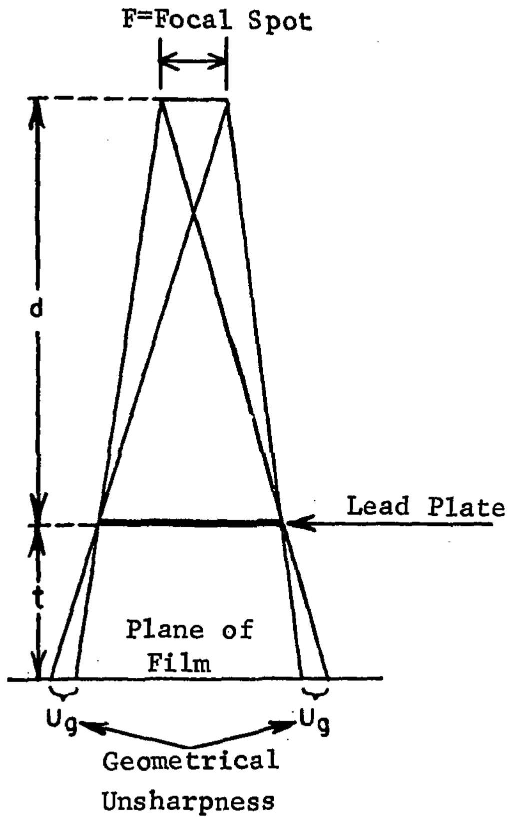

FIGURE V-4. GEOMETRIC DISTORTION DUE TO FINITE FOCAL SPOT(2)

NOTE: (Size $U_g = \frac{Ft}{d}$).

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Multiple Film Techniques

It is often necessary to radiograph a part which has two or more sections that differ widely in thickness. The imaging of these sections on a single film can be accomplished only by using a wide-latitude exposure; this results in low contrast. To overcome this problem, a multiple film technique is used in which two or more films, differing in relative film speed, are placed in the same cassette and exposed simultaneously. A faster film is used to image thick sections, while a slower film permits adequate inspection of thinner sections. The arrangement of the films is important, because the upper film offers some filtering to the lower one. By the proper combination of films, multisection objects may be successfully radiographed in one exposure.

Fluoroscopy

Fluoroscopy permits real time viewing of radiographic images. An exposure arrangement similar to that shown in Figure V-5 is used; the fluoroscopic screen emits visible radiation in response to the incident X-ray intensity. This technique is less sensitive than film imaging but it is useful where immediate results are needed and a permanent record is not required. However, recent advances in solid-state image amplification have resulted in the development of very sensitive radiographic techniques that closely resemble conventional fluoroscopy (see page V-16).

Stereo Radiography and Triangulation

A conventional radiograph provides only two-dimensional information about a three-dimensional object. Occasionally, the location of a discontinuity in three dimensions is helpful or even necessary to evaluate its criticality. To obtain this information, two relatively simple techniques are available: (1) stereo radiography, and (2) triangulation. In stereo radiography, two images of the object are made, one with the source shifted to the left of center and one with the source shifted to the right. The total shift is equal to the normal interpupillary distance. The two radiographs are then placed in a stereo viewer that permits the inspector to view the image of the object as though he were looking into the object. However, the depth determination is only qualitative and is subject to the viewer's subjective interpretation.

In triangulation, two exposures are made on the same radiograph as shown in Figure V-6. With this technique, geometric relationships are used to determine the depth of a given discontinuity. Markers are placed on the film side of the object being radiographed, and two exposures are made with a shift of the tube equal to the distance, a. By measuring the resultant displacement of the flaw image, b, the distance of the flaw above the film plane, d, can be determined with the equation:

$$d = \frac{bt}{a \pm b}$$

where

t = source-to-film distance.

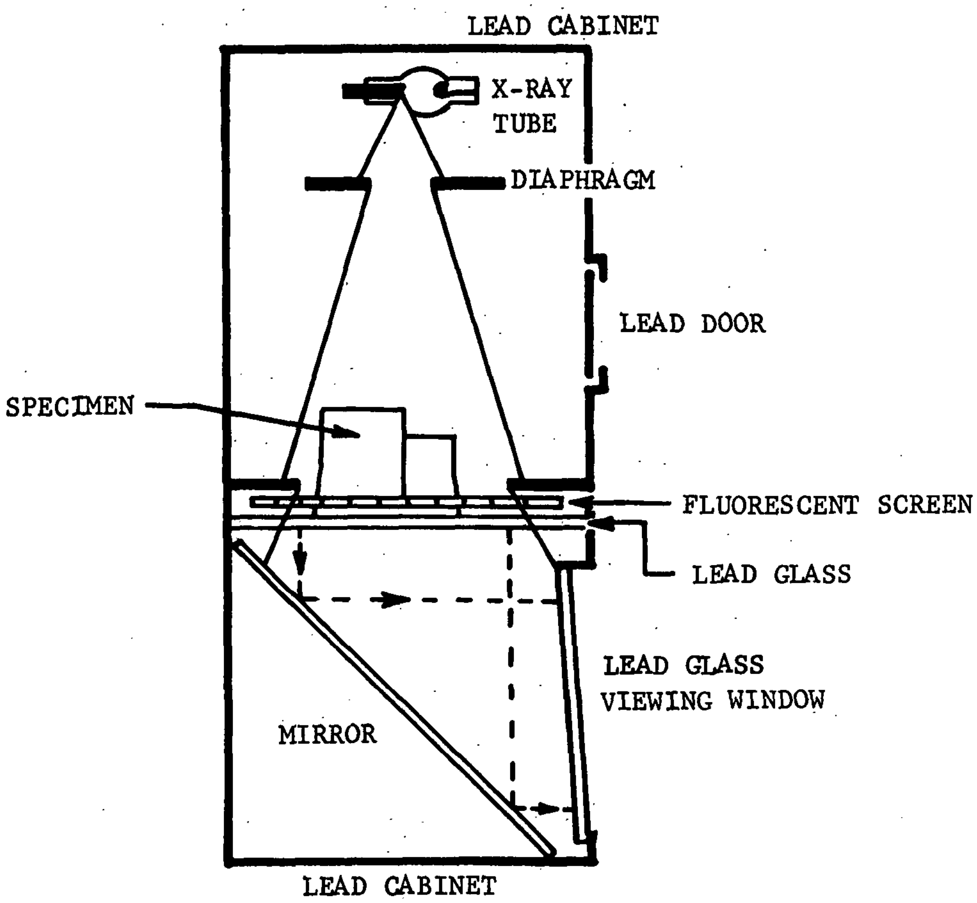

FIGURE V-5. TYPICAL FLUOROSCOPIC INSPECTION UNIT[1]

NOTE: Leaded glass protects inspector. Production line set-ups may provide conveyor belts, etc, for product transport.

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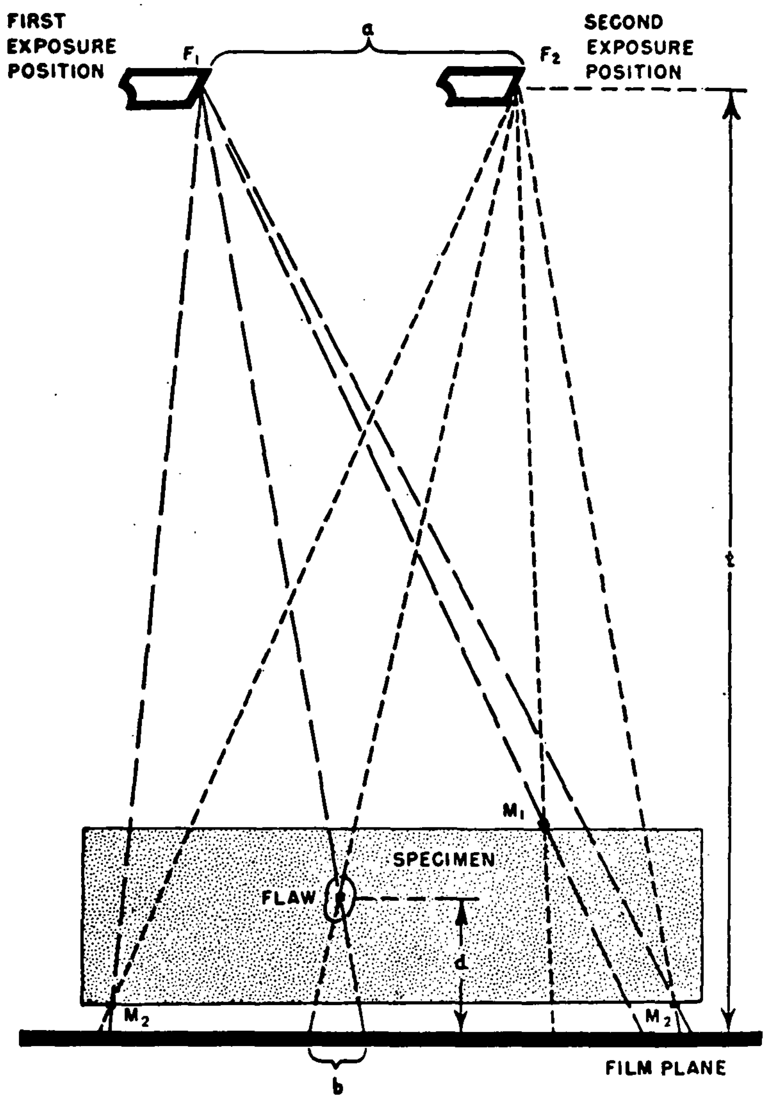

FIGURE V-6. RELATIONSHIP OF TUBE SHIFT AND IMAGE SHIFT IN TRIANGULATION TECHNIQUE FOR DEPTH LOCATION OF DEFECTS (2)

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Tomography

Tomography is a technique for developing an image of a single plane through a section by pivoting the X-ray source and film systematically about the plane of interest, so that information from all other planes is blurred. A simple illustration of this technique is shown in Figure V-7.

Thickness Measurements

X-ray methods may be useful in making thickness measurements. Although the mathematical development of a relationship between film density and thickness of an absorber is too complex for practical use, an empirical method of thickness measurement has proven useful. By imaging the object of interest and a step wedge of the same material on a single film, it is possible to obtain a good estimate of the thickness of a material section. This process has also found some use in the measurement of void dimensions. For best results, the section of interest and the step wedge must be placed as close to one another as possible to avoid variations in the uniformity of the X-ray output.

Geometric Enlargements

In instances where the focal spot size is extremely small, it is possible to separate the film and part to obtain an enlargement of a minute discontinuity. This technique has been used to produce enlargements up to three diameters, thus making otherwise undetectable indications visible. Extreme care must be exercised in the implementation of this technique, since a focal spot which is too large leads to a lack of sharpness and renders the results meaningless.

Microradiography

Microradiography is a special technique used to obtain detailed information about a thin section of material. For example, ultrafine-grained photographic emulsions which are generally deposited on glass plates can be used with relatively low voltages (5-50 Kev) to determine element distributions in alloys. Other uses include examinations of the fine structure of low-density materials and the measurement of very small dimensions. The microradiographs may be optically enlarged to obtain the detail required. A fine focal spot is required, and it is desirable to use an X-ray source which has low filtration at relatively low voltages. Sometimes, the use of low-density gas in a special exposure chamber will help reduce filtration.

Flash Radiography

Where it is desirable to "stop" a dynamic event by radiographic inspection, high-speed or flash radiography may be used. Equipment manufactured for flash radiography provides short (on the order of 10 nanoseconds) pulses of high-intensity radiation. Typical applications include the study of explosive events and of projectiles traveling at high velocities.

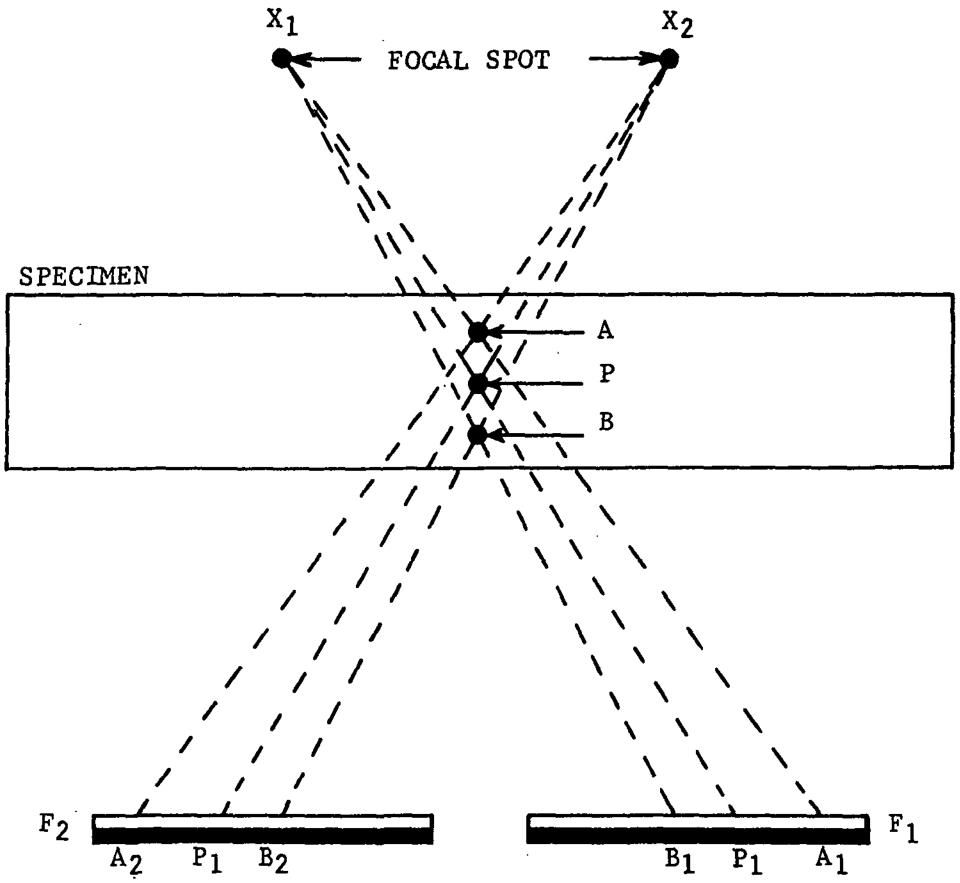

FIGURE V-7. SIMPLIFIED CONCEPT OF TOMOGRAPHIC IMAGING(1)

NOTE: Tube is shifted from X_1 to X_2 while film is moved from P_1 to P_2. Source and film rotate about a pivot point in the plane of interest. Relative distances have not been maintained in figure to simplify illustration.

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X-ray Diffraction

With this nondestructive testing technique, a crystal serves as a diffraction grating for X-rays. Measurements are used for the identification of crystalline solids and polymorphic forms, and have also been applied in measurement of residual stress.

New Developments

In recent years considerable work has been done to develop imaging techniques for radiography. For example, the X-ray vidicon television imaging system was developed for the inspection of solid-propellant rocket case walls and weldments.[4] An X-ray sensitive vidicon tube presents the results of X-ray inspection on a television monitor. The active area of the camera tube is approximately 1/2-inch x 5/8-inch and the image formed on this area may be presented on a 17-inch television monitor with an approximate 30X magnification. This system is capable of "in-motion" inspection of welds in plate up to 1/4-inch thickness at speeds up to 18-inches per minute with true two-percent penetrameter sensitivity and no loss of detail. Since its original development in the early 1960's, X-ray sensitive vidicon systems have been improved and are available as standard equipment from most major suppliers of X-ray equipment. The image intensifier is a similar device which provides a one-to-one readout of the input image via either an optical chain or a television monitor readout. This system is also capable of "in-motion" radiographic inspection.

Under NASA sponsorship, a solid-state image amplifier that provides the immediate readout capabilities of a fluoroscopic screen has been developed.[5] However, this device is much more sensitive than a conventional fluroscopic screen and produces images with more contrast and brightness. Solid-state image amplification techniques have also been used to produce a device that permits image retention for 10 minutes or more; the storage unit incorporates cascading image amplifiers.

A dry X-ray imaging technique has been developed using direct print, recording oscillograph paper.[6] Although this method has a relatively low-contrast sensitivity (about eight-percent), it is quick and useful in cases where the object to be inspected provides high object contrast. The use of this paper saves both time and material costs.

X-ray flaws have been mapped by computer graphics methods.[7] Using X-radiographs produced from two views and a microdensitometer with a digital computer, this technique permits the perimeter of a defect to be described in three dimensions. The technique sometimes provides ambiguous results which can be alleviated by the addition of a third view. However, in initial evaluation, the technique produced results that correlated well with actual metallographic sections. The use of this technique permits the inspector to make a reasonable judgment as to the criticality of a defect based on its shape and location.

Color radiography is also being investigated[8,9] and is expected to permit better definition of finer defects because of the added variables of hue and saturation. Improved visual perception of slight differences in input radiation intensity should serve to permit higher-sensitivity inspections. The CODE-R system[10] (color derivation extraction of X-ray radiographs) permits resolution of minute density differences. Although color radiography is rather expensive, it provides some increase in sensitivity and latitude, and its use by the aerospace industry for critical applications is expected.

Applications

Radiographic inspection is used extensively for the following purposes:

- Inspection of incoming material (e.g., forgings, castings, electronic components).
- Inspection of manufactured parts after various stages of fabrication (e.g., welding, forming, leachings, bonding, etc.).
- Inspection of final products.
- Maintenance inspection.

Radiography can generally provide useful data resulting from the inspection of a homogeneous material in which internal defects are of interest. Radiography is widely used for inspecting:

- Castings for shrinkage, microshrinkage, gas pockets, inclusions, blow holes and dross.
- Forgings for tears, bursts, internal cracking and pipe.
- Welded and brazed joints for porosity, lack of fusion, undercut, lack of penetration, detection of internal or external cracking, and detection of the presence of inclusions.

These techniques are commonly used after fabrication operations for certifying the quality of the final part; they are frequently used for maintenance inspection also.

High voltage radiography (using photon energies in excess of 1 Mev) has been used for the inspection of solid propellant in rocket motors.[11] A linear accelerator capable of producing radiations at energies from 8 to 25 Mev is used to detect separations between the propellant and the liner and to detect voids within the propellant grains.

The X-ray vidicon television imaging system is commonly used by the aerospace industry for the inspection of electronic components to assess their internal condition. The system operated by the Marshall Space Flight Center[12] is used primarily for the inspection of resistors, capacitors, diodes, transistors, and relays. Internal defects such as particle contamination, misalignment, mechanical damage and other anomalies can be detected. Because it provides a real-time image, the system is economical and permits rapid inspection of critical aerospace electronic components. Radiographic examination is a requirement for line certification, qualification, and conformance inspection for microcircuits of the highest reliability level used by NASA (NASA Publication NHB 5300.4(3E) "Radiographic Inspection", October, 1971).

Gamma radiometry has been used at NASA's Lewis Research Center for determining density variations in small unirradiated, clad UO_2 plates.(13) Measurements are made at fixed positions and variations may be calculated by use of a statistical analysis.

Laminography, developed for the inspection of multilayer, printed-circuit board, permits the imaging of a single plane of a material. This is accomplished by synchronously rotating the plane of the film and the plane of interest about a common inclined axis. This permits distinct imaging of a single plane while all other planes in the material are blurred over the film surface.(14)

Particle Radiation Methods

Radiations involving high-energy particles are capable of penetrating matter. Of principal interest are alpha and beta particles and neutrons. The alpha particle, a helium nucleus (two neutrons and two protons), has a short range and is not generally used in nondestructive testing. The beta particle, an electron, has a greater range than an alpha particle, and is most generally used for thickness measurements by either the transmission or beta back-scatter technique. Neutrons, the neutral particles of atomic nuclei, have relatively large penetration ranges in most materials and are used for neutron radiography and neutron activation analysis measurements.

Particle radiations, like photon radiations, are characterized by their energy and intensity. Energy level determines the penetrating power of a particle, while the energy density determines intensity. Neutrons lose energy due to elastic collision, and are finally absorbed by capture mechanisms. The mass absorption coefficients for thermal neutrons show a random distribution with atomic number, in sharp contrast to the monotonic variation of X-ray attenuation coefficients with atomic number (Figure V-8). Neutron radiography complements X- and gamma-radiography since neutrons have the capability to penetrate materials that are virtually opaque to photon radiation (e.g., lead) while they are absorbed relatively easily by materials transparent to photon radiation (e.g., hydrogeneous materials, boron-bearing materials, etc.). For example, neutron radiography may be used to inspect explosive devices for explosive content, even though the explosive is encased in a metal container. The neutron radiographic examination of pyrotechnic devices is discussed in Reference 16.

Neutron Radiography

The techniques for neutron radiography, although similar to those for X-ray imaging, involve some important differences. The parallel nature of beams for a bulk source (e.g., a reactor) eliminates problems related to source-film distance and focal spot size.

Wet and dry methods for neutron radiography are available. The wet method, used with a swimming-pool reactor, involves the submergence of the test object and transfer screen in the reactor pool. These parts are positioned in a bell jar which is purged with gas to eliminate water. This technique uses a beam port from the reactor core within the pool. The beam port

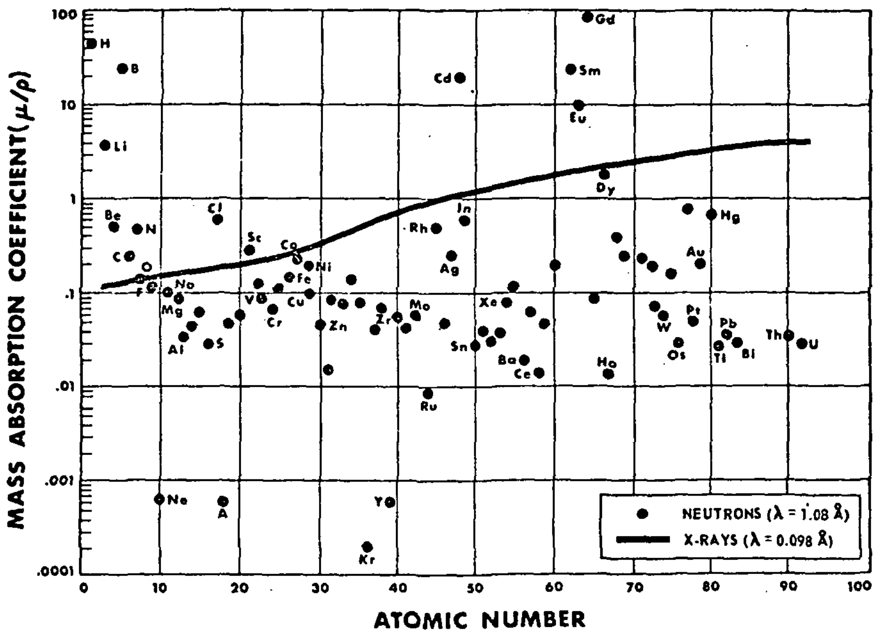

FIGURE V-8. COMPARISON OF X-RAY AND NEUTRON MASS ABSORPTION COEFFICIENTS[15]

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contains the moderator which slows the fast neutrons from the core to thermal energies. In the dry technique, a beam port from the reactor core is used externally.

Other than the differences already mentioned, the general procedure for making a neutron radiograph does not vary significantly from standard X-ray imaging methods. The object is positioned in the path of the neutron beam to meet requirements relating to defect orientation that are similar to those outlined for X-radiography. As shown in Figure V-9, either the transfer or the direct exposure method is used to detect the neutron image. Following exposure, the film is processed and interpreted in much the same manner as an X-radiograph.

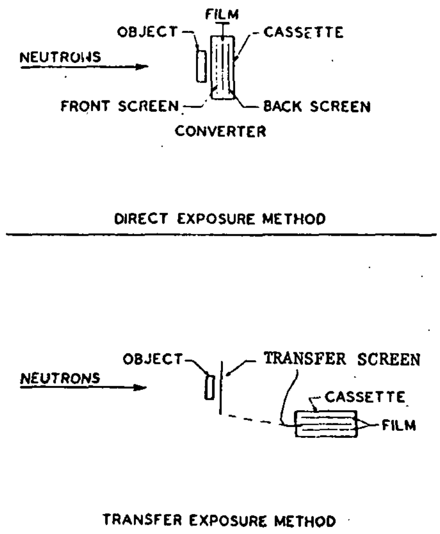

FIGURE V-9. SCHEMATIC REPRESENTATION OF THE DIRECT AND TRANSFER EXPOSURE METHOD OF NEUTRON RADIOGRAPHY[15]

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Neutron Activation Analysis

Neutron activation analysis is used to detect many trace elements in solids and liquids. When a material has been activated by neutron exposure, characteristic gamma emissions are produced. The detection and identification of these emissions permit identification and quantification of the activated elements which caused them. For example, this technique has been applied to detection of small amounts of trace element impurities in titanium.

Radiation Gaging Techniques

Radiation gaging techniques are used to rapidly determine the thickness of a section or a coating. The intensity of transmitted or reflected radiation is electronically monitored to determine that a section or coating thickness is within established limits. Many forms of radiation have been used for this purpose, including gamma-rays, X-rays, and beta particles, as well as some limited applications of neutrons. In all of these gaging methods, the transmitted or reflected energy intensity is compared with that from a known standard. In addition to production-line tests, these techniques have been used in laboratory measurements with resulting accuracies on the order of ±1/2 percent for thickness and density.

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Glossary

anode - The anode is the positively-biased electrode in an X-ray tube.

artifact - An artifact is a false indication on X-ray film that is not associated with the actual condition of the object under test; static marks caused by improper handling or fog resulting from improper film storage or processing are examples of artifacts.

autoradiography - Term used to describe a test in which the object being tested is radioactive or made radioactive, and the radiation from the object is used to produce an image on the film.

backscatter - Secondary radiations resulting from the interaction between the primary radiations from the source and the material; they are considered to have directions of travel greater than 90 degrees to the direction of travel of the primary radiation.

<u>betatron</u> - High-energy electron accelerator used to produce electrons with energies on the order of 10^6 to 10^7 electron volts. These high-energy electrons impinge on the heavy metal target to produce high-energy X-rays.

<u>bremstrahlung</u> - A term used to describe radiation loss due to acceleration of a charged particle by a nucleus.

<u>cassette</u> - A special holder used to protect X-ray film from exposure to light during radiographic exposure; in addition to the X-ray film, the cassette contains the screens, etc., used in association with the production of a radiograph.

<u>cathode</u> - Negatively-biased electrode of the X-ray tube.

<u>characteristic curve</u> - A curve of film density plotted as a function of log relative exposure; it is useful in establishing the proper exposure conditions relative to the radiation intensity.

<u>continuous spectrum</u> - Characteristic radiation pattern that exhibits energies for an unbroken series of frequencies over a wide range.

<u>contrast (on the film)</u> - Change in density that results from a given change in radiation input. Contrast is determined from the slope of the characteristic curve.

<u>contrast (radiographic)</u> - Density difference between the most dense and the least dense areas on a radiograph.

<u>contrast (subject)</u> - Difference in the amount of transmitted radiation through the most dense and least dense sections of the test object.

<u>curie</u> - Measure of radioactivity of an isotope. A curie is defined as that quantity of any radioactive material in which 3.70×10^{10} disintegrations per second are occurring.

<u>definition</u> - Measure of sharpness in the outline of the image of an object; the function of the types of screens, exposure geometry, radiation energy, and film characteristics.

<u>density</u> - Film density is defined by $d = \log \frac{I_o}{I}$

where d = density
I_o = light intensity incident on film
I = light intensity transmitted

<u>diffraction</u> - Physical process in which radiation is selectively transmitted or reflected in a given direction that is dependent on the lattice structure of a crystal; diffraction techniques are commonly used to study crystalline structures and are sometimes employed in the measurement of residual stresses.

<u>distortion</u> - Measure of the geometrical departure of an image from the true reproduction of the object.

<u>dosimeter</u> - Device that measures the amount of radiation to which a radiographer has been exposed.

<u>electron volt</u> - Unit of energy of penetrating radiation. The electron volt is the amount of energy gained by an electron when it is accelerated by a potential difference of 1 volt.

<u>exposure factor</u> - The product of current and time divided by distance squared for X-rays, and the product of curies and time divided by distance squared for gamma rays.

<u>film speed</u> - Measure of the response rate of film to a given amount of incident radiation.

<u>filters</u> - Sheets of materials (usually copper) which are used to remove the low-energy portion of radiation from a continuous X-ray spectrum; a filter is placed between the source and the object of inspection.

<u>filtration</u> - Measure of the inherent property of an X-ray generator to remove the low-energy portion of the radiation.

<u>flash X-ray</u> - Term used to describe the technique in which a tube capable of producing very short (10 to 100 nanoseconds), high-intensity pulses of radiation are used for special radiographic investigations.

<u>fluorescent screen</u> - Sheet of material which is coated with a substance that fluoresces when exposed to X-rays; it is placed in intimate contact with the film to enhance the effect of incident X-rays on the film.

<u>fog</u> - Type of film artifact which results from improper storage of radiographic film or from overdevelopment; a gray "foggy" background that causes loss of radiographic clarity.

<u>gamma ray</u> - High-energy photon that originates in the nucleus of an atom as the result of nuclear decay processes.

<u>half life</u> - Time required for the activity of a radioactive material to decay to half its original value.

image amplifier - Device that enhances a radiographic image for the purpose of decreasing interpretation time or increasing image detail.

intensifying screen - Sheet of material placed in intimate contact with the film which, due to interaction with the incident radiation, enhances the resultant image on the film (see fluorescent screen).

isotope - Name given to a set of atomic structures, all having the same Z (atomic) number but differing in atomic weight; in radiography, the term generally refers to an atomic structure which is unstable and decays to a stable configuration by the emission of energy in the form of gamma radiation.

kilovoltage - A measure of the maximum output of photon energy from an X-ray source; for example, a 150 kilovolt X-ray source is capable of producing a maximum energy of 150 kilo-electron volts.

laminography - Special form of tomography which is used for limiting an inspection to a single plane in the material; images of the condition along the plane of interest are brought into sharp focus, while other images are smeared or blurred.

latent image - Potential image which is stored in the form of chemical changes in the film emulsion and is brought out by development of the film.

linear accelerator - A linear accelerator is a device that is used to accelerate electrons. The electrons may then be impinged upon a heavy metal target to produce high-energy X-rays.

microradiography - Microradiography is a technique used to examine very small objects or minute detail through the use of low voltage X-rays and an ultra fine grain film emulsion which is examined with the aid of optical enlargement.

milliamperage - Milliamperage is a measure of the current flowing between the cathode and the anode in an X-ray tube. The output intensity of the radiation is a function of this current.

neutron radiography - Neutron radiography is a technique in which neutrons are used as the penetrating radiation to produce a radiography of an object.

penetrameter - A penetrameter is a specially designed metal shim used to assess the sensitivity and resolution achieved in a radiograph.

quality of radiation - The quality of radiation is a measure of its degree of penetration.

Glossary
(Continued)

<u>roentgen</u> - A roentgen is a measure of energy density for X-rays and gamma rays and is defined as the quantity of X-rays or gamma rays which produces ions carrying 1 e.s.u. of charge per 0.001293 gram of air.

<u>scatter</u> - Scatter is a term used to describe secondary radiation which is emitted in all directions.

<u>specific activity</u> - Specific activity is the activity of a source measured in curies per unit weight.

<u>undercut</u> - Undercut is a term used to describe excessive radiation intensity which may be found at the edge of an object. Undercutting is usually associated with scattered radiation.

<u>unsharpness</u> - Unsharpness is a term used to describe the lack of definition of an edge due to geometrical factors related to the source size and the source-to-film distance.

CHAPTER VI

ULTRASONICS

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CHAPTER VI

ULTRASONICS

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CHAPTER VI

ULTRASONICS

Introduction

Ultrasonic testing involves observation of the interaction of high-frequency sound waves with the part being inspected. The ultrasonic wave travels with little loss through homogeneous materials, but it is interrupted and reflected by discontinuities. Its behavior (velocity, magnitude, and direction) is dependent on the density and elastic properties of the material. The frequencies used for inspection are above the audible range and vary from 20 KHz to 1,000 MHz; however, most field testing is performed between 1 and 25 MHz.

Scope

In general, ultrasonics may be applied to both metals and nonmetals, providing these materials have reasonably low acoustic attenuation factors. With proper selection of frequency, transducers, and wave mode, this method can be used with materials whose thicknesses range from a few microns to many feet. Under favorable inspection conditions, ultrasonics may be used for the following purposes:

- Detection of surface and internal voids and inclusions in homogeneous, welded, and brazed structures.
- Determination of elastic properties of materials.
- Measurement of material thickness from one side.
- Detection of unbonded areas in honeycomb and composite structures.
- Determination of strength of adhesive-bonded joints.
- Detection of gross corrosion on internal surfaces.
- Determination of residual stress distribution.

Advantages and Disadvantages

The major advantages of ultrasonic inspection are:

- High sensitivity: Very small defects can be detected under favorable conditions.
- Great penetrating power: Thicknesses up to 30 feet in steel can be inspected.
- Accurate defect location: Three-dimensional location of a defect can be determined accurately and defect size can be estimated.

- Fast response: Speed is limited by the ability to couple the transducer to the part being inspected.

- Minimum accessibility requirements: Access to only one surface is needed.

The major disadvantages are related to:

- Unfavorable sample geometry: Size, contour, complexity, and defect orientation can limit ability to detect defects.

- Undesirable microstructure: Large grain size, excessive porosity and inclusion content, and dispersed precipitates can limit defect detection.

Basic Principles[1,2]*

Ultrasonic sound waves are generated and introduced into a specimen using electromechanical transducers which convert electrical energy into mechanical energy and vice versa. Piezoelectric transducers are used at frequencies above 200 KHz. Piezoelectric crystals expand or contract when an electric potential is impressed across two opposing faces. Conversely, a stress applied to the two faces produces an electric potential across them. During inspection the transducer is placed in intimate contact with the surface of a test specimen and excited into oscillation. The sound wave is transferred into the material where it is propagated away from the contact area at a speed dependent upon the density and elastic properties of the material. The various types of transducers in use are discussed in a later section.

Ultrasonic Waves

The ultrasonic energy is propagated in two principal modes: (1) longitudinal or compressional when the oscillations are parallel to the direction of wave travel; and (2) transverse or shear when the oscillations are perpendicular to the direction of the wave travel. This second mode can be further divided into three subtype waves: (1) shear, (2) surface (Love and Rayleigh), and (3) plate (Lamb).

The relationship between frequency (f), wavelength (λ), and velocity (V) is given by the expression

$$f \lambda = V.$$

As the wavelength decreases, the ideal condition of rectilinear propagation is approached. However, as indicated below, some spreading occurs during propagation:

$$\mathrm{SIN}(\emptyset) = 1.2\ \lambda d$$

* Superscript numbers refer to References shown at the end of this Chapter.

where

ϕ = beam spread

λ = wavelength

d = energy source diameter.

If the transmitting frequency is decreased until the wavelength approaches the energy source dimensions, the waves will propagate in all directions.

The reflection and transmission characteristics of an ultrasonic wave striking the interface between two mediums at some minimum critical angle are shown in Figure VI-1. If the incident beam is a longitudinal wave, the first refracted wave is a shear wave and the second is a longitudinal wave. The amount of energy reflected is determined by the acoustic impedance of each of the two mediums. For example, for a water-to-steel boundary, 88 percent of the incident ultrasonic energy is reflected and 12 percent is transmitted; for an air-to-solid interface, 100 percent of the incident energy is reflected. When the velocity in the second medium is larger than that in the first, it is possible to have an incident or critical angle that produces a 90-degree angle of refraction. At this angle, a surface wave is generated and the ultrasonic energy does not penetrate into the second medium.

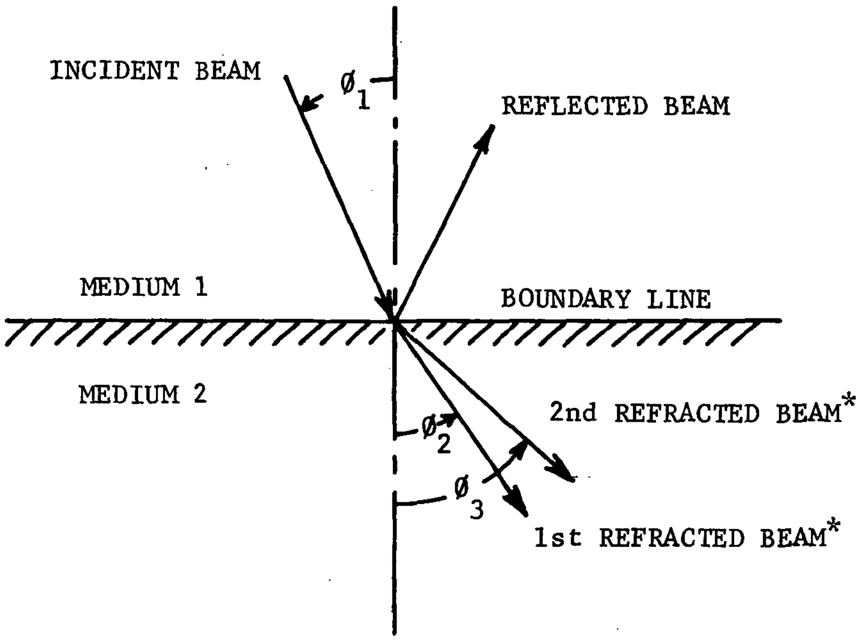
Ultrasonic Transducers

Transducers convert electrical energy to mechanical energy, and vice versa. During inspection the ultrasonic energy is transmitted from the transducer to the material by: (1) holding the transducer in intimate contact with the material surface, (2) cementing the transducer to the surface, or by (3) using a liquid or semiliquid couplant that wets both the transducer and the surface of the material. The last of these is the most commonly used technique. For best results, the acoustic impedance of the couplant should approach that of the material to be inspected.

The three piezoelectric materials most commonly used in the production of high-frequency ultrasonic transducers are quartz, lithium sulfate, and polarized ceramics (barium titanate, lead metaniobate, and lead zirconate titanate). The characteristics of these materials are reviewed below:

(1) Quartz. Quartz has excellent chemical, electrical, and thermal stability, is insoluble in most liquids, and is very hard and wear-resistant; it also has good uniformity and resists aging. Unfortunately, it is the least efficient generator of acoustic energy of the commonly used materials. It also suffers from mode conversion interference and requires high voltages to drive it at low frequencies.

(2) Lithium Sulfate. Lithium sulfate transducers are the most efficient receivers of ultrasonic energy, but are intermediate as generators. They do not age and are little affected by mode conversion interference. However, lithium sulfate is fragile, soluble in water, and limited to use at temperatures below 165 F.



* If the incident beam is a longitudinal wave, the first refracted wave is a shear wave and the second is a longitudinal wave.

FIGURE VI-1. REFRACTION AND MODE CONVERSION AT ANGULAR INCIDENCE

(3) Polarized Ceramics. The polarized ceramic transducers are the most efficient generators of ultrasonic energy; they operate well on low voltage, are practically unaffected by moisture, and are usable at temperatures up to about 300 C. They are limited by relatively low mechanical strength, some mode conversion interference, and a tendency to age.

The design of a transducer requires a compromise among several factors and varies with each application. The basic considerations are (1) the piezoelectric crystal, (2) the electrode type and configuration, (3) the backing material, and (4) the frontal member. The electrodes provide a means for applying a voltage gradient across the piezoelectric crystal. The gradient usually takes the form of a large pulse lasting for less than 10 μ sec; it causes ultrasonic energy to be developed in the crystal. The backing material places a load on the crystal and dampens ringing; it has a significant effect on transducer performance. Maximum damping occurs when the impedance of the backing material equals that of the crystal. A frontal ceramic wear plate is generally added to the transducer to protect the piezoelectric crystal from environmental conditions and, in some cases, to function as a lens to shape the beam of ultrasonic energy.

Ultrasonic energy can be focused using lenses as an integral part of the transducer assembly to reduce and control energy loss. In most applications, the lens concentrates the ultrasonic energy into a long, narrow, cigar-shaped beam, thus increasing its intensity. The advantages of using focused transducers are:

(1) Increased sensitivity to small defects

(2) Increased resolution

(3) Reduction in effects of surface roughness

(4) Reduction in effects of object contour.

The sensitivity of a transducer is a measure of its ability to detect and receive echoes (reflected vibrations) from small defects within a material. Transducer sensitivity is generally determined by the measured amplitude response from an artificial defect in a standard reference block. The resolution, or resolving power, of a transducer refers to its ability to separate two defects positioned close together at a certain depth. For example, small defects just beneath the surface of the test material are difficult to resolve, because the echo received is usually masked by the initial transducer ringing.

Contact or immersion inspection techniques require the same transducer construction for both shear-mode or longitudinal-mode transducers. The shear mode is usually developed from piezoelectric crystals operating in the longitudinal-mode but producing an angular incidence upon the surface of the test material leading to a partial or total conversion of the longitudinal wave into a shear wave.

Ultrasonic transducers are classified as either normal or angle beam. With the normal or straight-beam transducer, the ultrasonic waves are normal to the radiating surface. In an angle-beam transducer, a wedge-shaped (usually Lucite) material is placed between the test material and the piezoelectric crystal. With this transducer, the waves are refracted at the interface and penetrate obliquely into the material. Figure VI-2 illustrates both types of transducers.

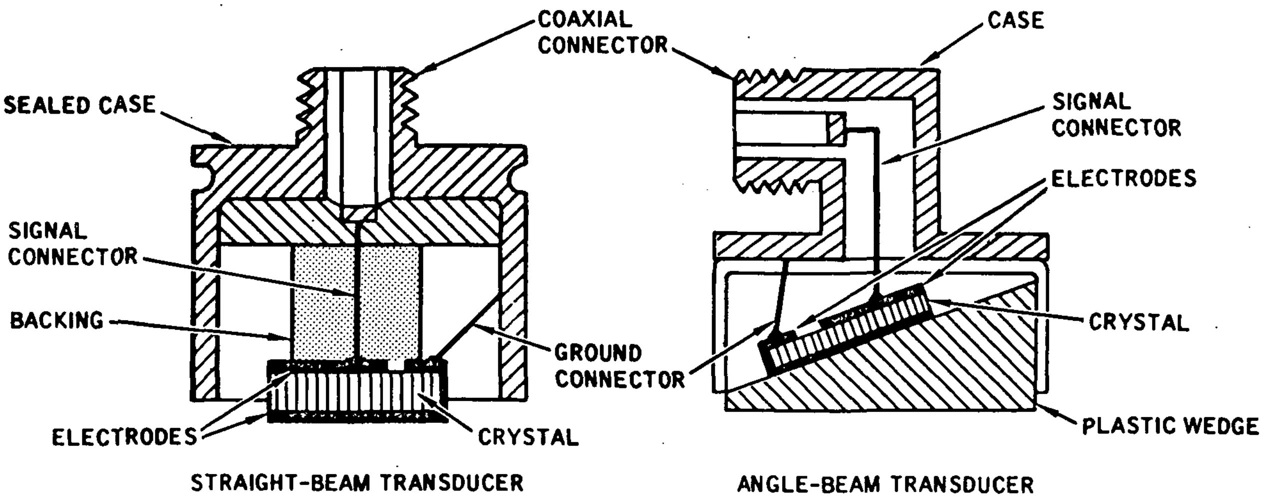


FIGURE VI-2. STRAIGHT-BEAM AND ANGLE-BEAM TRANSDUCER

Reprinted from: "Ultrasonic Testing: Classroom Training Manual", NASA CR-61228, National Aeronautics and Space Administration, Huntsville, Alabama (January 1, 1967).

Transducers are made in a wide variety of sizes and shapes. The larger the transducer, the less the beam spread for a given frequency. The large transducers transmit more sound energy into the test material and are used to gain deeper penetration. The narrower beams of small high-frequency transducers have greater ability to detect small discontinuities. Higher frequency systems use thinner crystals and have greater sensitivity. Most ultrasonic testing is done at frequencies between 0.2 and 25 MHz, but contact testing is generally limited to about 10 MHz because the crystals that are ground for use above 10 MHz are too thin and fragile for practical use. Special double transducer units are commonly used with one crystal being the transmitter and the other the receiver. The crystals may be mounted side by side for normal-beam testing and stacked or paired for angle-beam testing. In all cases, the crystals are separated by an absorbent sound barrier material to block cross interference.

Procedures

Contact Testing

In contact testing, the transducer is placed in direct contact with the surface of the specimen. The transducer is coupled to the material through a thin layer of couplant, usually a liquid or paste. In most cases, the inspector manually manipulates the transducer by scanning the area to be inspected while observing reflected signals on the oscilloscope screen of the ultrasonic instrument. If a defect is found, he must manually scan the questionable area and use human judgment to mark its location. Success, scanning speed, and accuracy are clearly dependent on the operator's ability to recognize and resolve defect indications. Alarms are sometimes used to alert the inspector to suspected defects.

Immersion Testing

In immersion testing, both the transducer and test material are immersed in a liquid couplant (usually water with a rust inhibiting agent added). The transducer does not touch the specimen and the ultrasonic energy is transmitted to the material through the liquid. Generally, the crystal is mounted on the end of a scanning tube which is attached to a manipulator that permits flexibility in controlling position of the transducer relative to the test material. The manipulator is commonly attached to a carriage with provisions for moving the assembly along the top of the scanning tank.

Test Methods

The three basic testing methods are (1) pulse-echo, (2) through-transmission, and (3) resonance.

Pulse-Echo. In this method, a pulsed ultrasonic beam is transmitted through the couplant into the test material. At the opposite face, the beam is reflected and the echo is picked up by the transducer; the transmitting transducer may be used for this purpose or a separate receiving transducer may be used. A defect will also reflect back an echo. The elapsed time between the initial pulse and reflected echoes is measured with a cathode-ray oscilloscope. A defect is identified in terms of the relative position and amplitude of its echo. The problem of identification may be complicated by multiple reflections displayed within the echo pattern. Signal resolution depends on the duration of the ultrasonic pulses; shorter pulses are used for thinner materials.

Through-Transmission. The through-transmission method requires two transducers, one functioning as a transmitter and the other on the far side of the material functioning as a receiver. As in pulse-echo testing, short pulses of ultrasonic energy are transmitted into the material. The receiving transducer which is aligned with the transmitting transducer receives the ultrasonic energy that passes through the material. The quality of the material being tested is determined by the energy lost as the ultrasonic wave propagates through the material.

Resonance. Resonance testing requires a tunable, variable-frequency, continuous-wave oscillator to drive the transducer. When the specimen thickness is such that its resonant frequency corresponds to that of the oscillator, the specimen will vibrate in resonance; this occurs whenever the thickness of the specimen is equal to an integral number of half wavelengths of the ultrasonic wave. When resonance occurs, an increase in energy drawn by the transducer is indicated by a suitable meter or by an oscilloscope. The resonance technique is commonly used for thickness measurements and for the detection of internal corrosion and delamination.

Data Presentation

A-, B-, and C-scan techniques are used to present the results of ultrasonic testing of materials. Most test instruments use A-scan presentation as shown in Figure VI-3. The horizontal base line on the cathode-ray tube (CRT) screen indicates elapsed time (from left to right) and the vertical scale shows the signal amplitudes. For a given ultrasonic velocity in the specimen, the sweep can be calibrated directly in terms of distance or depth. Conversely, when the dimensions of the sample are known, the sweep time can be used to determine ultrasonic velocities from which elastic moduli can be calculated. The signal amplitudes represent the intensities of transmitted or reflected beams. These may be related to flaw size, sample attenuation, and beam spread.

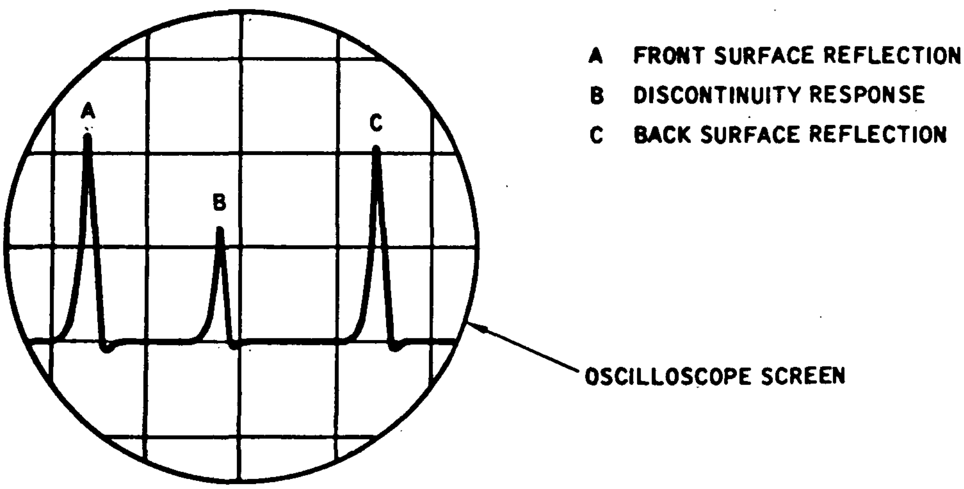


FIGURE VI-3. A-SCAN PRESENTATION

Reprinted from: "Ultrasonic Testing: Classroom Training Manual", NASA CR-61228, National Aeronautics and Space Administration, Huntsville, Alabama (January 1, 1967).

The B-scan displays a cross section of the material along a line showing top and bottom profiles of the material being tested. A B-scan presentation system is illustrated in Figure VI-4. A C-scan presentation system which displays a plan view of the test material is illustrated in Figure VI-5. Clearly, the B- and C-scan systems require the synchronization of CRT traces with the motion of complex scanning mechanisms and require long persistence screens and sophisticated circuitry.

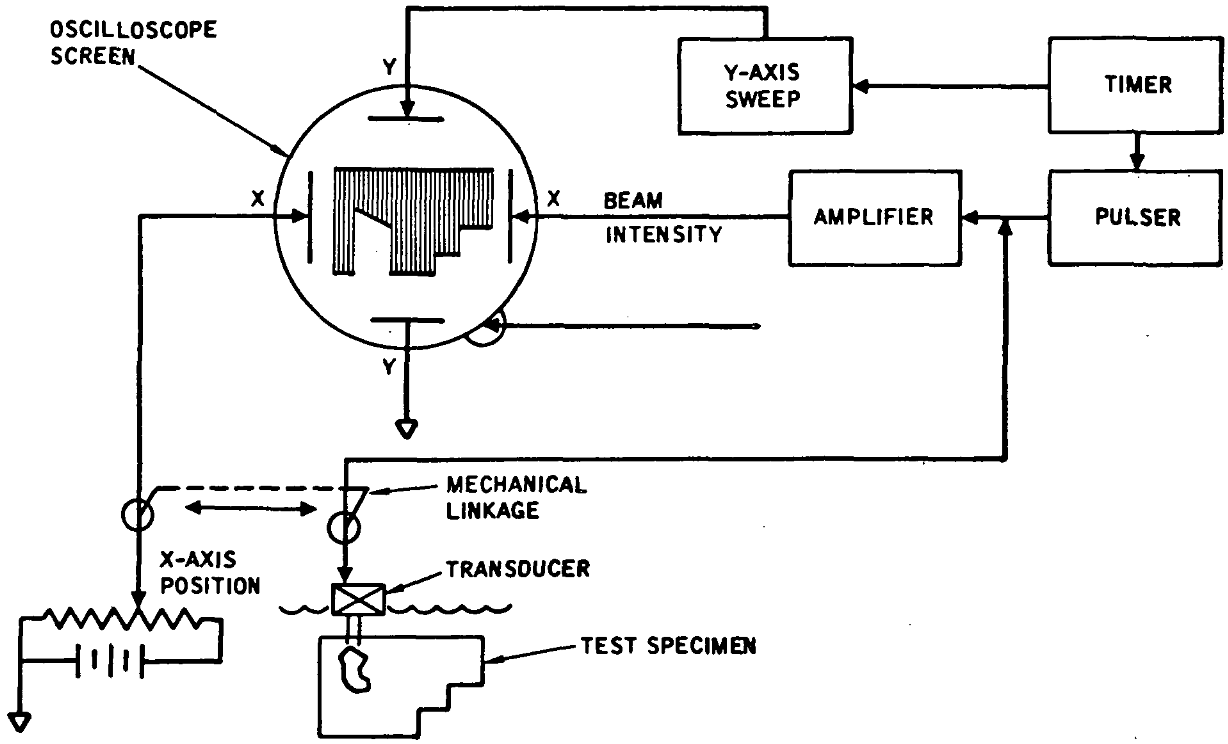


FIGURE VI-4. B-SCAN PRESENTATION SYSTEM

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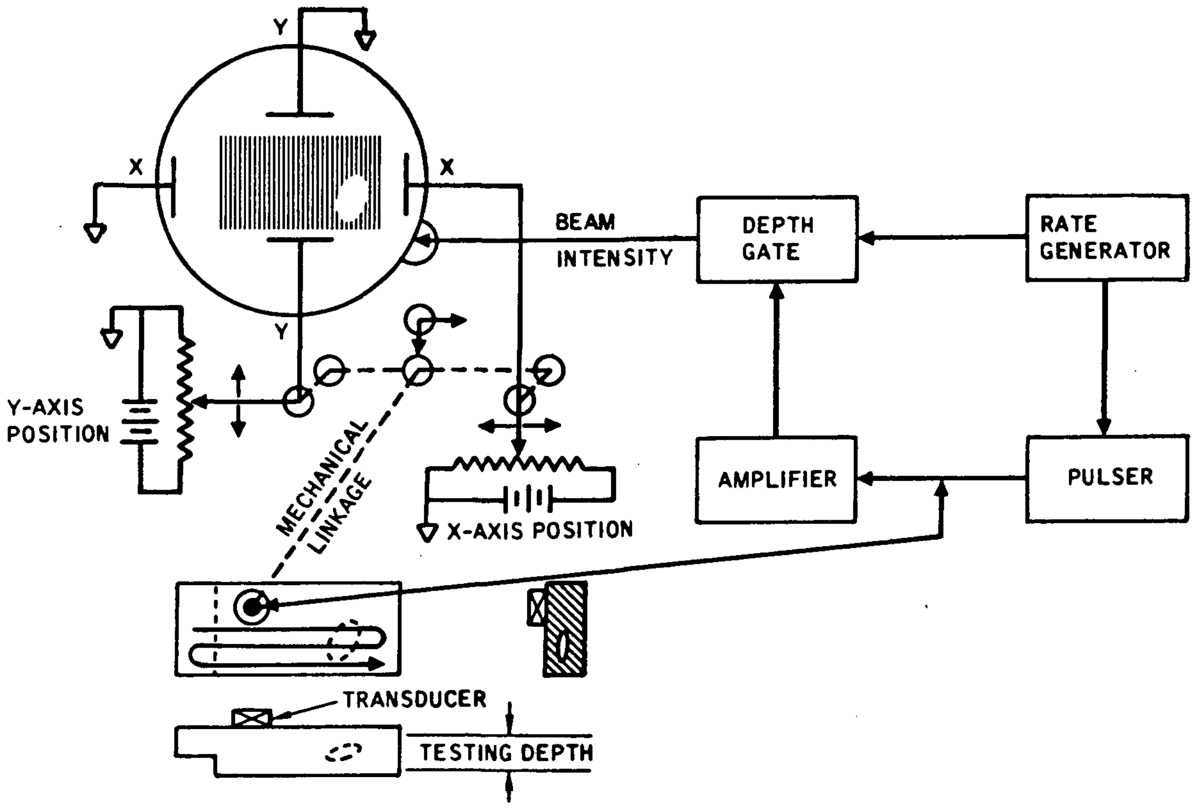

FIGURE VI-5. C-SCAN PRESENTATION SYSTEM

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Influence of Test Material and Defects

Surface Conditions. As indicated below, angular, contoured, and other irregular surface conditions can cause a number of undesirable effects:

(1) Loss of the reflected defect signal.

(2) Loss of the back-reflection signal.

(3) Increased width of the front-surface reflected signal.

(4) Loss of resolving power.

(5) Distortion of the wave directivity.

(6) Occasional generation of unwanted surface waves.

Attenuation. Energy losses can also be caused by attenuation within the material; these consist of scattering and absorption losses. Scattering is caused by partial reflection of the sound at each of the small grain boundary interfaces through which the sound must pass as it propagates through the material. Absorption losses are caused by the damping of the sound beam due to atomistic effects. Generally, attenuation losses increase with frequency.

Defect Characteristics

The orientation and depth of a defect may cause confusing indications and result in the loss of a defect signal. The defect signal varies as the angle of reflectance from the defect changes, and may cause the reflection to be directed away from the transducer in some instances. Indications are also affected by the depth of the discontinuity and the resulting variations in beam characteristics and attenuation.

The shape of a defect affects the ultrasonic beam in much the same way as material interfaces and boundaries. A defect having a rough surface tends to scatter the reflected energy, while a smooth surface defect reflects a more direct ultrasonic wave.

Variations in the acoustic impedance of the defect also affect the magnitude of the signal received. For example, a crack, void, or seam is a material boundary with a high acoustic impedance, and almost total reflection of the signal occurs. Slag, a nonmetallic inclusion, has an acoustic impedance closer to that of the test material than a void has. Since some of the energy propagates through the inclusion, a lower amplitude defect signal is obtained.

Equipment

Ultrasonic testing equipment varies in size and type, depending on the specific application. The equipment for the most commonly used technique, pulse-echo, consists of the ultrasonic instrument and the transducer.

Battery-powered portable instruments are used where ease of mobility is desired (e.g., for field testing). These instruments can be used to perform either contact or immersion tests. The instrument contains three major components: power supply, pulser/receiver, and display/timer. The power unit provides electrical current for all instrument functions, and may be supplied from a line source or from a self-contained battery unit. The pulser or pulse generator is the source of high-energy bursts which are triggered by a timer and applied to the transducer. Returning pulses are received, amplified, and delivered to the display unit, usually an oscilloscope with a sweep generator, marker generator, and the necessary controls to provide a visual image of the received signals.

Most units for immersion testing consist of a bridge and manipulator which are mounted over a water tank in such a manner as to support a pulse-echo testing unit and an X-Y recorder as shown in Figure VI-6.

An ultrasonic resonance instrument has a self-excited oscillator circuit for changing the frequency; the transducer is connected to the plate or anode of the oscillator tube. If the oscillator is tuned to a resonant frequency of test material, the amplitude of the transducer vibrations will peak. This increases the loading of the transducer and produces an increase in plate current that can be indicated on a meter. Various forms of resonant instruments which use the ultrasonic method for thickness gaging and flaw detection are commercially available. These instruments differ primarily in the method and width of frequency modulation and in the type of presentation.

Reference Standards

In practice, reflected signals received from defects are generally compared to standard reference samples; such reference blocks are available in a variety of types and materials. They contain real or artificially induced defects in the shape of notches and holes. Before any ultrasonic test is performed, the equipment should be calibrated using the established standard.

Parameter Selection

The parameters involved in ultrasonic testing can be divided into different groups: (1) operator-controlled parameters, and (2) parameters determined by the specific application. Operator-controlled parameters that relate to equipment selection and operation are:

(1) Instrument type

(2) Transducer type and size

(3) Technique; pulse-echo, through-transmission, or resonance

(4) Coupling method: contact or immersion

(5) Data presentation: A, B, or C-scan

(6) Control settings: frequency, pulse length, and rejection level.

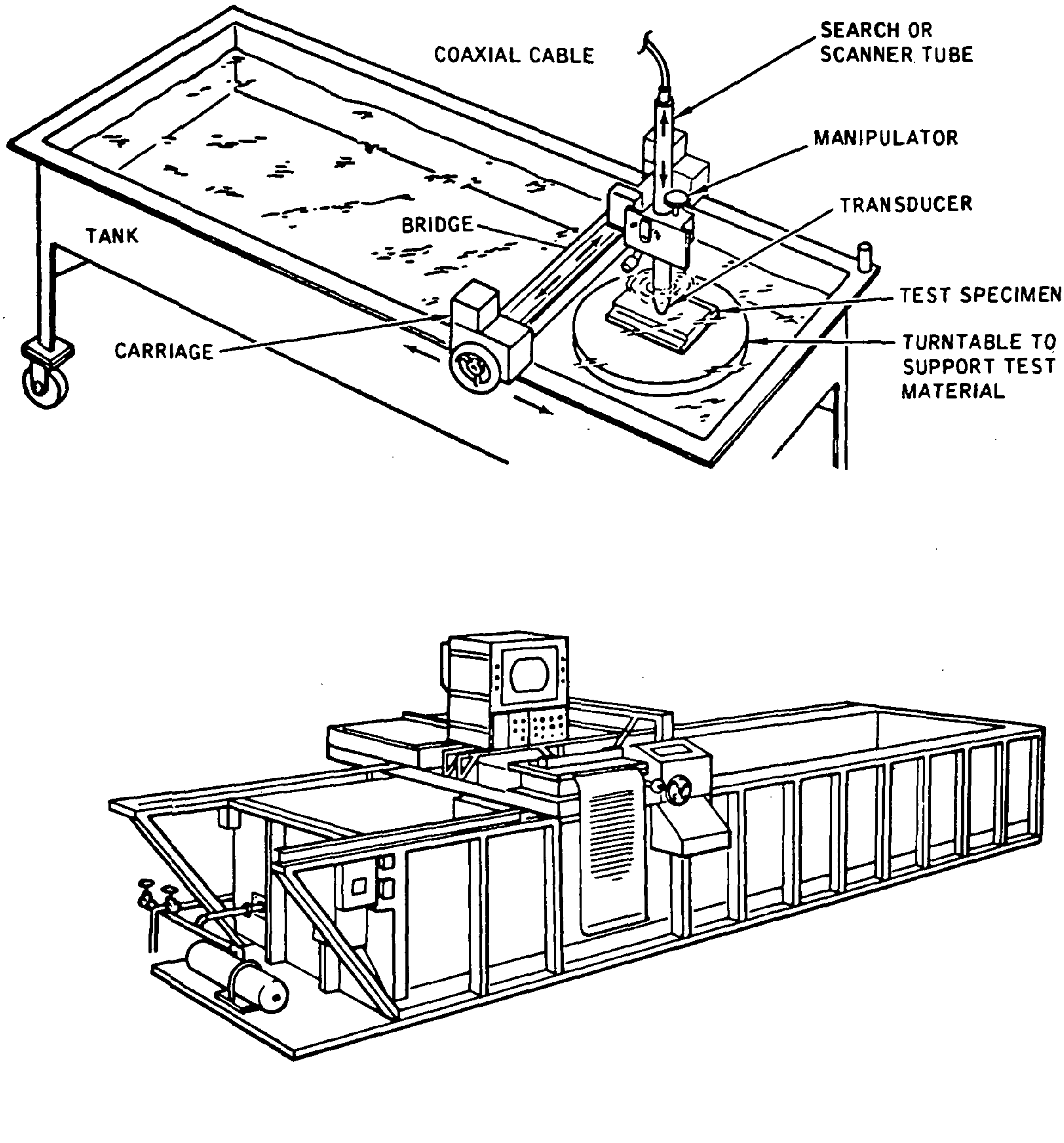

FIGURE VI-6. ULTRASONIC IMMERSION TANK AND BRIDGE/MANIPULATOR

Reprinted from: "*Ultrasonic Testing: Classroom Training Manual*", NASA CR-61228, National Aeronautics and Space Administration, Huntsville, Alabama (January 1, 1967).

Parameters determined by the specific inspection application are:

(1) Velocity

(2) Impedance

(3) Geometry

(4) Surface condition

(5) Attenuation

(6) Defect: size, shape, and orientation.

The principal parameters that should be established before each test are noted below:

(1) Selection of the proper operating frequency; this is governed by the material characteristics and the type of defect. Higher frequencies are more sensitive to defect size, but produce less penetration.

(2) Selection of the proper transducer type and size on the basis of the material characteristics and size of defect. The larger the area of the defect in relation to the cross-sectional area of the ultrasonic beam, the greater the reflection from the defect.

(3) Selection of the proper wave mode as indicated by orientation of the defect and geometry of the test part. The longitudinal-wave mode is generally used for defects parallel to the surface of the material. The shear or transverse-wave mode is generally used to locate defects perpendicular or nearly perpendicular to the surface.

New Developments

Research and development has been directed toward improving ultrasonic inspection equipment and techniques.

Flaw Detection, Location, and Analysis

A triangulation system has been developed to locate and identify defects with the use of a transmitting and one or more receiving transducers.[3] All transducers are dry coupled to the workpiece by pressure. Acoustic wave guides impart an angular sweeping motion to the transmitted acoustic beam without physical movement of the contacting probes. By triangulation techniques, the location of the intersection area of the transmitted acoustic beam and the direct line to the receiving transducer is continuously determined with a computer. A flaw at the intersection area scatters the energy detected by the receiving transducer, and the presence and location of the defect is instantly recorded. The technique is applicable to simple structures such as cylinders or flat plates, but it has limitations on more complex structures where intervening interfaces or reflecting surfaces are present.

Delta Technique

The Delta technique[4-6] is based on the principle that acoustic waves impinging on the boundary of a defect cause the boundary to oscillate so that the defect, in essence, becomes a source of acoustic energy which is reradiated over a wide angle. A shear wave is transmitted into the part with an angle transducer, and a receiving transducer is positioned normal to the surface at a fixed distance from the transmitter. Since a portion of the reradiated energy is normal to the surface regardless of the orientation of the defect, the technique is much less sensitive to defect orientation than the standard pulse-echo technique. Tests have demonstrated the successful detection of defects in aluminum alloy weldments at inspection rates of 50 feet per hour. Lack of penetration (0.030" X 0.060" in size) and lack of fusion as narrow as 0.025" were reliably detected. Microfissuring (laminar shrinkage defects) in 3/16" and 1/4" thick welded sections were detected where radiographic techniques failed because of unfavorable defect orientation.[4]

Imaging

Acoustic imaging techniques convert the acoustic response into a visual display. Four general classes, depending on the mechanism employed, are: chemical, thermal, optical, and electronic.[7]

(1) The chemical methods include the use of photographic film and materials with specially coated surfaces which produce an image through a variation in density or a contrasting color change that results from the impingement of ultrasonic energy. With the exception of the photographic film technique, these tests involve immersion in special solutions to obtain reasonable results. These techniques require energy levels that are orders of magnitude higher than those required with standard piezoelectric transducer tests.

(2) With thermal methods, the heat generated by the impinging acoustic energy is measured by thermocouples or thermopiles or by changes in such material characteristics as conductivity or photoemission. Also included are those techniques in which surfaces with special coatings that change color or luminesce in the presence of heat are used. These methods are relatively insensitive in comparison with those involving standard piezoelectric transducer techniques.

(3) The optical methods of most interest are the schlieren and holographic techniques. With the schlieren technique, a collimated light beam is passed at right angles to the direction in which the ultrasonic beam travels in a liquid. The ultrasonic waves cause periodic changes in the index of

refraction of the liquid in its path, so that an image of the profile of the beam is formed. The technique is applicable to both continuous wave and pulsed transmission. When used with pulsed transmission, a stroboscopic light source is used to permit the pulse to be stopped in any desired "location" or to travel at a velocity suitable for visual observation. The technique does not produce an image of a defect but is useful for studying beam behavior.

Acoustic holography uses the same principle as optical holography to obtain a visual image of a defect. In one method the object is "illuminated" by an acoustic beam from one transducer and the acoustic image is focused on the surface of a liquid.[8] At the same time, the surface is "illuminated" by a reference acoustic beam from a second transducer. The result is a hologram formed on the surface of a liquid as the result of variations in the elevation of the liquid surface which are caused by the impingement of the acoustic waves. The surface performs the same function as the photographic film does in optical holography. The surface is illuminated by light, and the image is viewed directly or photographed through a special filter.

Another holographic method detects acoustic energy with a scanning-point piezoelectric transducer.[9] The electrical signal modulates a light source mounted on the transducer housing. The light is then used to produce a standard optical hologram which is a representation of the acoustic pattern. Direct energy or energy scattered from a defect may be used.

(4) The electronic methods have the greatest sensitivity to acoustic energy and include the standard techniques of detecting acoustic energy with a piezoelectric transducer and displaying it by means of A, B, or C-scans. Permanent records of the A-scan signal can be made on a commercial videotape recorder; oral comments by the inspector can be recorded simultaneously. Several different styles of ultrasonic cameras have been investigated; they incorporate a piezoelectric material which receives the acoustic energy. The back of the piezoelectric element is scanned by a beam and a visual image is produced and displayed in much the same manner as television.

Of the new imaging techniques, only the schlieren, holographic, and ultrasonic cameras have been used in a limited way for special applications. The requirement for immersion testing has inhibited use of these innovations.

Applications

In addition to the conventional uses of ultrasonic testing techniques that have been indicated earlier in this Chapter, these techniques have been used for many special applications.

(1) Detection of surface and internal voids and inclusions in welded and brazed structures.

(2) Determination of elastic properties of materials.

(3) Measurement of material thicknesses from one side.

(4) Detection of unbonded areas in honeycomb and composite structures.

(5) Determination of strength of adhesive-bonded joints.

(6) Detection of gross corrosion on internal surfaces.

(7) Determination of residual stress distribution.

Aerospace Applications

Instances in which ultrasonic testing procedures have been used by the aerospace industry are discussed below:

Fasteners and Honeycomb Structures. Acoustic techniques have been applied to detect concealed cracks in installed fasteners and fastener holes and to locate disbonds in honeycomb structures.[10] The effect of the defect on damping characteristics at a particular frequency were used as the means of detection.

Brazed Joints. A pulse-echo technique has been used to detect lack of bonding in brazed tube joints of rocket engine components.[11] A transducer was inserted in a water filled tube to scan the inside surface. The reflection from a lack-of-bond area indicated the presence of a defect.

Solid Propellant Rocket Motors. Lack of bonding and poor bond quality between casing and liner and between liner and propellant have been determined with pulse-echo techniques.[12-14] In one case, the amplitude of the recovered signal indicated the character of the defect. In another, the decay rate of the recovered signal was used as the means of detection.

Fuel Tanks. The presence of intergranular corrosion on the inside surface of welded joints has been detected using a pulse-echo technique in which a transducer was mounted in a liquid-filled wheel being rolled parallel to the joint.[15] The amount of energy absorbed determined the degree of corrosion.

Honeycomb Panels. The presence of unbonded areas in various types of adhesive-bonded honeycomb has been determined using pulse-echo and through-transmission techniques.(16) The recovered energy is analyzed for amplitude, damping, or phase changes to detect the presence and location of the defective areas.

Other Applications

Brief discussions of a few special applications are presented below:

In-Process Spot-Weld Monitoring. In this application, the through-transmission technique was used with the transmitting transducer on one electrode and the receiving transducer on the opposite electrode. The amplitude of the received signal which was plotted versus time showed a characteristic signature for an acceptable weld. The acceptable tolerance from the ideal condition was represented by parallel areas on each side of the ideal trace. All welds whose traces fell outside the allowable tolerance were unacceptable. Typical traces of acceptable and unacceptable welds are illustrated in Figure VI-7.(17)

Crack Growth Monitoring. Sub-critical crack growth during fatigue and stress-corrosion investigations has been monitored.(18) The loading of the specimen and the location of the ultrasonic transducer is illustrated in Figure VI-8. After a crack has been started, a normal transducer is positioned on the face parallel to the crack growth direction, and it is moved horizontally until a portion of the beam intercepts the crack and gives a response of a certain amplitude. As the crack grows, more of the beam is intercepted and the response tends to increase in amplitude. However, a servo-type system moves the transducer in the direction of crack growth to maintain the response amplitude at the initially established height. The rate of transducer movement is a direct measure of the rate of crack growth.

Determination of Elastic Properties. Since the propagation of ultrasonic energy is dependent on the elastic properties of a material, the dynamic Poisson's ratio of a material can be determined by measuring the velocity of the longitudinal and shear wave modes.(19) The relationship between the three are expressed in the following equation:

$$\frac{V_s}{V_L} = \frac{1 - 2\sigma}{2\,(1 - \sigma)}$$

where

V_s = shear wave velocity

V_L = longitudinal wave velocity

σ = Poisson's ratio.

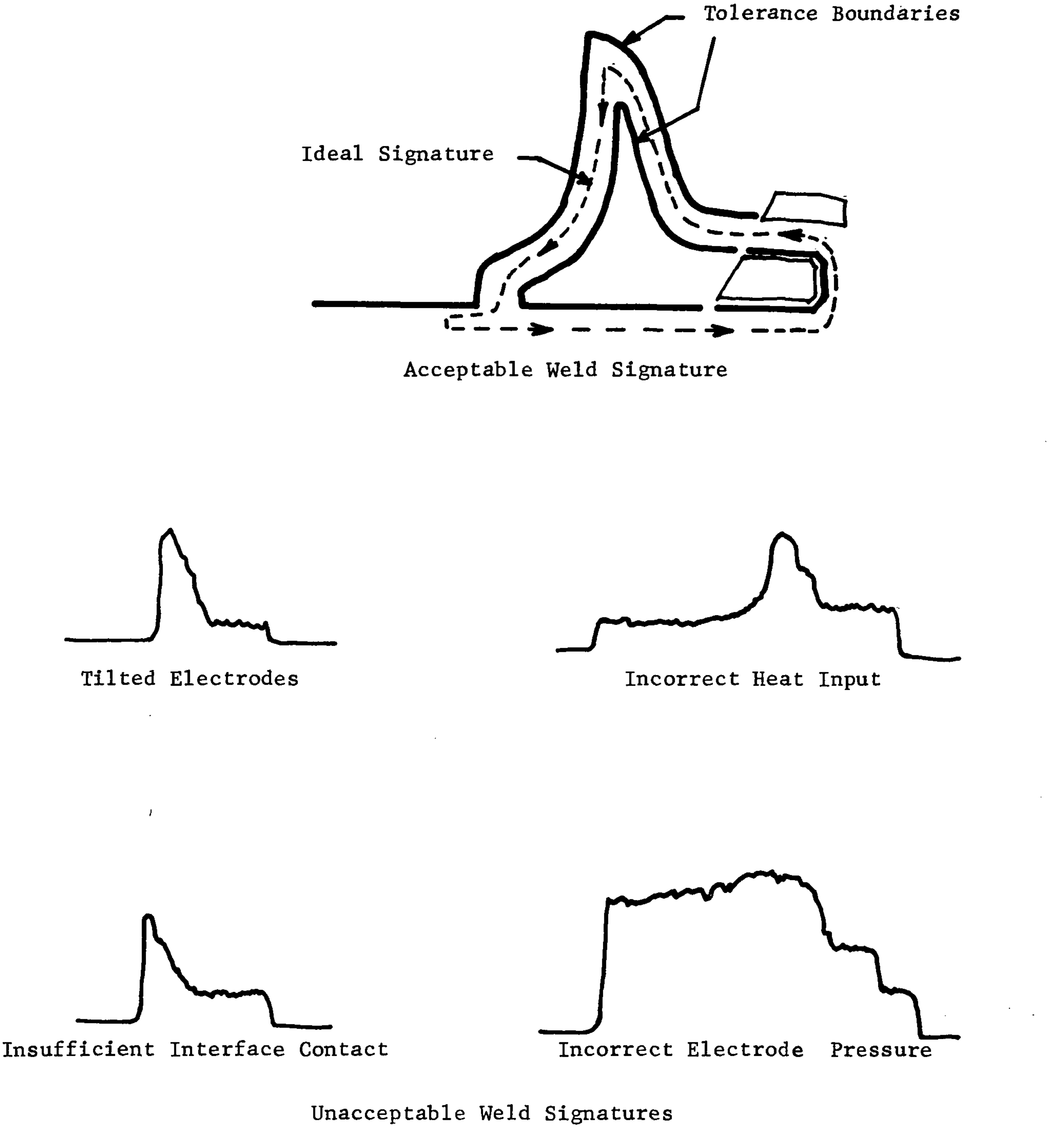

FIGURE VI-7. ULTRASONIC TRACES OF IN-PROCESS SPOT-WELD MONITORING[17]

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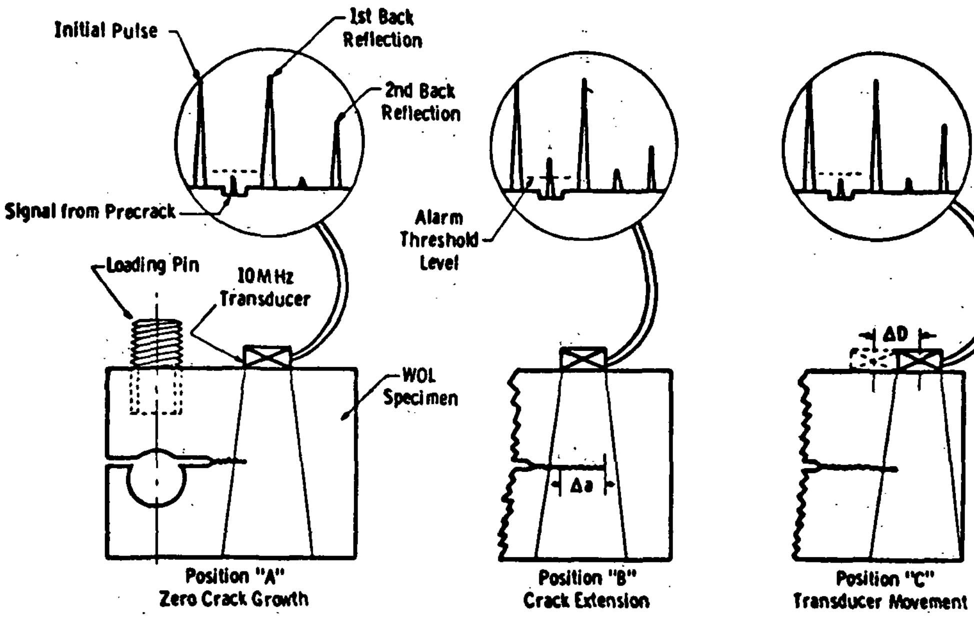

FIGURE VI-8. ULTRASONIC TRACES DURING CRACK-GROWTH MONITORING(18)

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Other elastic constants can be obtained by relationships between the velocities of the two wave modes and the density. This has been done in the case of graphite where density was determined by radiometric means and equated to ultrasonic wave velocity. The following equation defines the Bulk Modulus:

$$K = V_L^2 \, p - 3/4\mu$$

Young's Modulus:

$$Y = V_L^2 \, p \, \frac{(1 \pm \sigma)\,(1 - 2\sigma)}{1 - \sigma}$$

Shear Modulus:

$$\mu = V_s^2 \, p$$

where

p = density (and the other symbols have been defined).

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Glossary

<u>A-scan display</u> - A cathode ray tube display where the received signal is displayed as a vertical excursion from the horizontal sweep trace; the horizontal separation of any two signals is a measure of the distance between the two conditions causing them.

<u>angle-beam transducer</u> - A transducer that transmits or receives the acoustic energy at an acute angle to the surface.

<u>attenuation</u> - The loss in acoustic energy that occurs between any two points of travel. This loss may be due to absorption, reflection, refraction, etc.

<u>B-scan display</u> - A cathode ray tube display where the signal from a discontinuity is displayed as an illuminated spot. The face of the CRT represents the area in a vertical plane through the material. The display shows the location of a discontinuity as it would appear in a vertical section view through the thickness direction of the material.

<u>back reflection</u> - The signal that represents the reflection from a surface being used as a reference surface.

<u>C-scan display</u> - A chart recorder display where the discontinuity is displayed as a contrasting area against a constant background. The area of the chart represents the area of the surface scanned by the transducer. The display shows the location of a discontinuity as it would appear in a plan view of the material.

<u>contact transducer</u> - A transducer that is coupled directly to the surface of the material or to the surface through a thin film of couplant.

<u>cross talk</u> - The signal generated by a portion of the acoustic energy going directly from the transmitting crystal to the receiving crystal without propagating along the intended path through the material.

<u>discontinuity</u> - The generic name for any condition that is a departure from the normal characteristic of the material being inspected. It may be a change in thickness, a void, a variation in composition, etc.

<u>far field</u> - The region beyond the near field where discrete regions of high and low acoustic intensity do not occur.

<u>focused transducer</u> - A transducer that incorporates an acoustic lens that converges the acoustic beam to a focal point or line at a definite distance from the face.

<u>immersion transducer</u> - A transducer that is coupled to the surface of the part by a liquid couplant path. It is used for inspections where the transducer and surface are immersed in liquid or where the acoustic path is a stream of liquid flowing between the transducer and the surface.

Glossary
(Continued)

interface - The physical boundary between two adjacent surfaces.

Lamb wave - A type of acoustic energy propagation that travels along the surface of a material and in which the oscillation of the molecules are nominally at right angles to the surface.

longitudinal mode (compressions) - A type of acoustic energy propagation in which the oscillations of the molecules of the material are nominally perpendicular to the direction of travel.

mode - The manner in which acoustic energy is propagated through a material as characterized by the form of oscillation of the molecules of the material.

mode conversion - The characteristic of the surface to change the mode of propagation of acoustic energy from one form to another.

near field (Fresnel) - The region extending from the face of a transducer outward where the interaction between spherical wave fronts emanating from different points on the face of the transducer create discrete areas of high and low acoustic intensity.

piezoelectric phenomenon - A characteristic of certain crystalline and ceramic materials to expand or contract when an electrical potential is applied to opposite faces. They will also generate an electrical potential across opposite faces when stress is applied to those faces.

Rayleigh wave - A type of acoustic energy propagation that travels along the surface of a material and in which the oscillations of the molecules are nominally elliptical.

reflection - The characteristics of a surface to reflect or change the direction of propagating acoustic energy.

refraction - The characteristic of a material to change the direction of acoustic energy after it has passed through an interface.

repetition rate - The rate at which the inidividual pulses of acoustic energy are generated.

resolving power - The measure of the capability of an ultrasonic system to separate two discontinuities at slightly different distances from the transducer.

scanning - The relative parallel motion between a transducer and a surface.

send/receive transducer - A transducer containing two crystals mounted side by side separated by an acoustic barrier. One generates the acoustic energy and the other receives it.

sensitivity - The measure of the capability of an ultrasonic system to detect small discontinuities.

shear mode - A type of acoustic energy propagation in which the oscillations of the molecules in the material are nominally at right angles to the direction of wave propagation.

straight-beam transducer (normal transducer) - A transducer that transmits or receives the acoustic energy at right angles to the surface.

transducer (search unit) - An assembly consisting basically of a housing, piezoelectric crystal, backing material, wear plate, and electrical leads for generating and/or receiving acoustic energy.

void - The generic name for a class of mechanical discontinuities where there is a physical separation between opposing walls.

CHAPTER VII

EDDY CURRENTS

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CHAPTER VII

EDDY CURRENTS

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CHAPTER VII

EDDY CURRENTS

Introduction

Electromagnetically induced, closed path alternating currents (eddy currents) in a material are used to evaluate material soundness and/or properties. Eddy current strength is sensed as impedance changes in the coil used to produce the currents or in a separate sensing coil.

Eddy current strength varies with material conductivity, permeability, dimensions, and homogeneity. For example, a crack alters the current path and changes the strength of the field sensed by the test coil. Similarly, a change in material thickness causes the eddy currents to be confined to a smaller volume and changes the test coil response.

Scope

Eddy current testing is sensitive to the following material characteristics:

- Alloy composition
- Hardness or heat-treated condition of steel
- Metallurgical structure and grain size
- Depth of hardened case in steel
- Presence of impurities, inclusions, segregation
- Internal stresses.

Eddy current inspection is applicable only to electrically conductive materials, either magnetic or non-magnetic. Since it has limited penetrating capability, this technique is applicable only to thin materials or for surface and near-surface conditions in thick materials.

To be detectable, a defect must intercept the flow of eddy currents. Thus, defects that lie in a plane parallel to the coil which produces the currents are not detectable. As a result, this approach is unsuitable for evaluating the bond between cladding layers or for detecting laminations in plate.

Advantages and Disadvantages

The major advantages of this inspection technique are indicated below:

- Fast. Very high inspection rates are feasible; for example, rod can be inspected for surface defects at 100 to 200 feet per minute.

- Automatic. Inspection can be automated so that defective parts are identified by marking or are rejected from the line.
- Portable or Semiportable. Small units are available for field use.
- No expendable material used.
- No personnel danger or hazards.
- Noncontact. No contamination of part.

The major problem with the eddy current inspection technique is its sensitivity to many different variables. Surface conditions (roughness, finish, contaminants), temperature, and relative position of the part can cause false readings. Small changes in conductivity due to minor structural variations can be a problem also.

Basic Principles[(1)*]

Eddy currents are circulating electrical currents that are induced in an electrical-conducting substance by a varying (usually an alternating) electromagnetic field. When a test coil excited by an alternating current is placed near a conducting material, an alternating magnetic field is generated and eddy currents are induced in the material. These circulating currents obey Lenz's law and flow in a direction opposing the alternating field of the test coil. This counteracting field is sensed by measuring the impedance of the test coil or of a secondary pickup coil.

Figures VII-1 and VII-2 illustrate two basic types of electromagnetic coupling. In Figure VII-1, the test material is passed through an encircling coil. The induced currents circulate in a circumferential direction. This type of coil is used with pipe, wire, rod, and extruded parts for continuous automatic inspection. Figure VII-2 shows the coupling of a probe coil that is used to induce currents which circulate in the volume of material immediately beneath the probe. The probe coil is used for both hand inspection and automatic scanning. A third type of coil is similar to the encircling coil; it is called an internal coil and is used to inspect the inside surfaces of tubing or drilled holes.

The four basic material characteristics measured by the eddy current method are: (1) electrical conductivity, (2) magnetic permeability, (3) dimensions, and (4) homogeneity.

The eddy current method is considered to be primarily useful for surface inspection, because the induced currents seldom penetrate more than 1/2-inch into the material being inspected. The effective or useful depth of

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* Superscript numbers refer to References shown at the end of this Chapter.

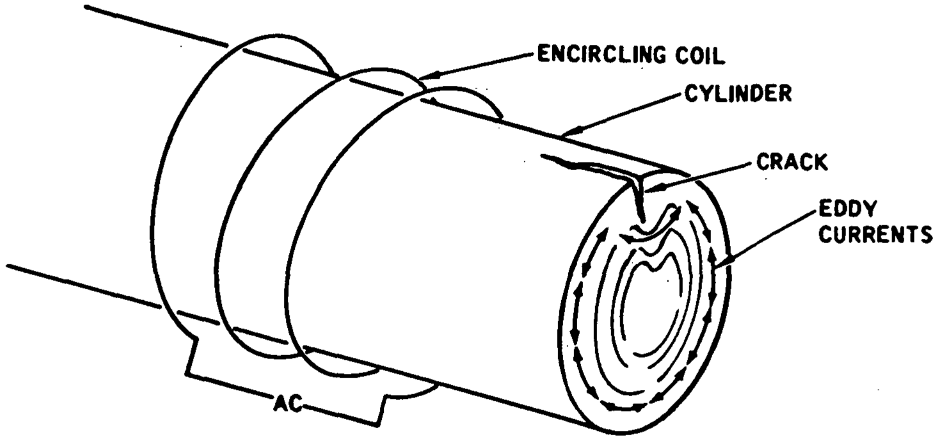

FIGURE VII-1. ENCIRCLING COIL

Reprinted from: "Eddy Current Testing: Classroom Training Manual", NASA CR-61230, National Aeronautics and Space Administration, Huntsville, Alabama (January 1, 1967).

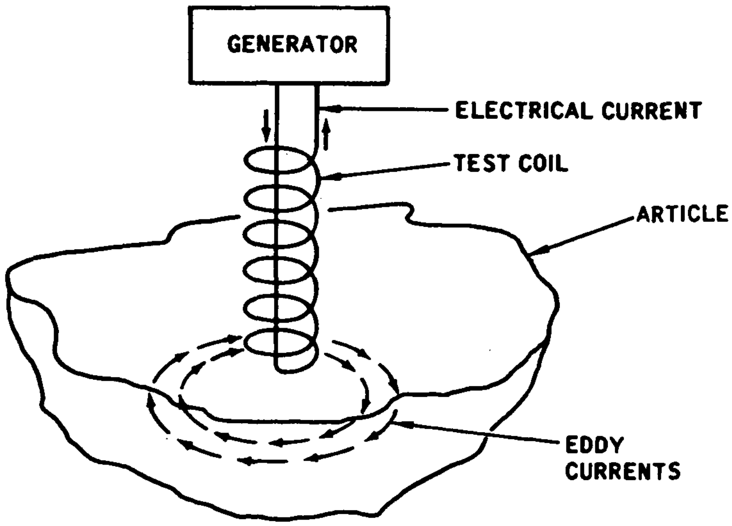

FIGURE VII-2. PROBE COIL

Reprinted from: "Eddy Current Testing: Classroom Training Manual", NASA CR-61230, National Aeronautics and Space Administration, Huntsville, Alabama (January 1, 1967).

penetration is the distance from the surface to a location in the part where the electromagnetic field strength falls off to 36.8 percent (1/e) of its surface value. Depth of penetration is inversely proportional to the square root of frequency. Test frequencies range from 10 Hz to 10 MHz; the band from 50 KHz to 200 KHz is most commonly used.

Changes in area, thickness, and surface contour are usually detectable by eddy current methods. To provide basic and useful information, studies have been conducted to determine the effect of geometry as well as conductivity and permeability on the impedance of basic test coil configurations.(2)

Since eddy current inspection is very sensitive to material properties, there is a major problem in discriminating between signals caused by inherent (or acceptable) material variables and those caused by defect conditions. Thus, signal-to-noise ratio (signal power divided by average noise power), is important to measurement reliability. If this ratio is less than about 3, the probability of erroneous test results is high.

Equipment

System Components

The basic eddy current inspection system involves five elements: (1) excitation unit, (2) matching block, (3) test coil, (4) signal processor, and (5) readout device(s). These units are discussed below.

(1) The excitation unit, a signal generator or oscillator, provides the alternating voltage required to energize the test coil. Although the excitation voltage is usually a single frequency sinusoidal wave, pulsed square waves and superimposed sinusoidal waves are also used to enhance capabilities to process the signals and for other purposes.

(2) A matching block electronically matches the test coil to the excitation source. A matching network can be as simple as a single resistor inserted in series with the test coil to produce a change in impedance that is reflected as a change in voltage at the test coil terminals. However, most eddy current systems employ a bridge network where the fixed voltage across the test coil is nulled so that very small changes in impedance can be detected. Small defects can lead to changes on the order of 0.01 percent of the total test coil impedance. The bridge network allows these signals to be amplified to detectable levels.

(3) Signal processing equipment varies, depending on the nature of the inspection application. Most systems contain amplifiers followed by detectors of various types. The amplifier increases the magnitude of attenuating voltage received from the test coil circuitry. A detector circuit then converts the alternating voltage to a D-C voltage which can be applied to additional signal processing circuitry or directly to the readout portion of the system.

(4) Once a signal which reliably indicates the change in the variable of interest is produced, a number of devices such as markers, signal lights, and chart recorders can be employed to either call attention to the change or record it for further analysis. However, it should be noted that most readout devices are effectively low-phase filters and tend to retard response.

Discrimination Techniques

When the test coil is scanned at a fairly constant speed, the detected output is often filtered to select the signal response caused by certain flaws. For example, a longitudinal crack in a section of tubing will cause a fairly abrupt change in the signal output of a circumferential scanning system. Band pass filters transmit these rapidly varying signals and reject the slower varying signals associated with temperature change and dimensional differences along the length of the tube. However, if spurious variables and acceptable flaws produce similar responses, they cannot be separated by filtering techniques.

Phase discrimination is also used to enhance signals associated with the variable of interest. In practice, phase discrimination is usually effective in reducing unwanted variations in the coil-to-test part distance. However, if the phase angle between the output for a variable of interest (e.g., flaw) and a spurious variable (e.g., surface scale) is small, phase discrimination becomes ineffective. Furthermore, in any case where there are three or more variables with different phase angles, there is no phase reference that will allow complete elimination of unwanted signals.

Procedures

Test specimen variables and changes in environmental conditions can significantly influence the performance of a particular eddy current inspection system. Test coil design (coil type, size, number of turns, etc.), test coil excitation (wave form and frequency), and signal processing electronics (response filtering, phase discrimination, and multifrequency variable separation) must be selected to best fulfill specific inspection requirements. The selection and/or modification of an eddy current inspection system should be based on a combination of experience, experimentation, and calculation. In particular, the variables associated with the parts being tested should be studied in order to maximize the signal-to-noise ratio. Commercially-available and custom-designed eddy current devices can be obtained to satisfy specific needs.

The selection of the test coil is influenced by the geometry of the part being inspected, accessibility to the surface, allowable inspection time, and the nature of the test variables. The last factor is usually the most important and, particularly, when the variable of interest is a flaw, the test coil should be designed to provide maximum response to this variable. In some cases, signals caused by other variables can be reduced by clever test coil design, filtering, and/or phase discrimination.

Important test coil design parameters are size, shape, number of turns, and core material (in the case of a probe coil). Test coil size is determined primarily by the distribution of the variable of interest and by physical restrictions. In flaw detection, the test coil size is largely determined by the size of the flaw. For probe coils, coil diameter is a key parameter while length is usually less important. However, for encircling coils, length can have a significant effect on resolution and signal response. Coils can be made for complex geometries and can be shaped to fit into tight places to obtain better electromagnetic coupling. Ferrite cores are often used with probe coils to concentrate the flux in specific areas and provide better coupling.

Theoretically, the number of turns of wire should have relatively little effect on basic performance. Thus, a ten-turn coil should reflect the same percentage impedance change as a thousand-turn coil. However, test coils with few turns present problems in instrumentation, because their impedance is small and more amplification is needed to provide detectable signals. On the other hand, coils with many turns may limit performance because of the interaction of the test coil inductance with the capacitance of the connection cable and with the capacitance between coil windings.

Frequency is selected to provide the greatest signal response to a change in the variable of interest; the required depth of penetration must be considered also. For example, when measuring the thickness of metallic cladding, the frequency should be selected so that the depth of penetration is comparable to the cladding thickness. The excitation frequency sometimes has a noticeable effect on defect resolution, since the electromagnetic flux associated with low frequencies tends to reach beyond the immediate vicinity of the test coil. A higher frequency tends to promote a slightly better resolution in the detection of surface variables. The scanning rate must also be considered during frequency selection. According to Shannon's theory[(3)], the test coil must be excited at a frequency which is greater than twice the frequency of the desired coil response. In practical terms, the test coil frequency should at least be equal to the scanning rate.

Eddy current testing is used most often with nonmagnetic materials. The use of this inspection technique with ferromagnetic materials is difficult, because the high permeability of these materials leads to spurious signals. A bias field can reduce permeability-related noise. To reduce permeability, a static magnetic field, nominally several thousand gauss, is applied to the ferromagnetic material in the vicinity of the test coil. This is usually accomplished with a large encircling coil energized by direct current or by the use of cross magnetization pole pieces of high permeability material energized by isolated coils.

Handling equipment can have a significant effect on variations in spacing between the test coil and the material (i.e., liftoff). Wobble and vibrations in the test material often cause significant problems in automatic inspection. The careful design and application of the handling equipment can minimize mechanical noise signals.

Time-response differentiation employs a scanning process to filter the output response to separate variables. If the variables have the same rate of response, it is difficult to separate their signals by this technique.

The dual coil eddy current system involves two test coils used to inspect adjacent areas simultaneously. The coils are connected in the matching network so that the difference between the two signals is obtained. This technique is similar to time differentiation in that abrupt variations produce output signals, whereas distributed variables are cancelled by signal subtraction. For example, two encircling coils can be used in a dual coil system to detect slivers in steel rod. The coils are designed and spaced so that the leading coil will be coupled to the edge of the sliver while the second coil is presumably coupled to good material. An output signal will be produced under these conditions. On the other hand, a gradual change in the diameter of the rod or in the chemistry will not tend to produce a signal output, since both test coils see practically the same change. The adjustment of spacing between test coils along with careful test coil design is essential. Although it is difficult to design identical coils which will provide uniform coupling or to resolve critical alignment and positioning problems, the dual coil technique can be combined with other signal processing techniques (e.g., phase discrimination and time differentiation) to alleviate some of these problems.

Perhaps the principal limitation of the dual coil and time-differentiating systems derives from the inability to make absolute measurements. Relatively homogeneous properties of the test material, such as conductivity, hardness, and thickness, cannot be determined with these techniques.

New Developments

Multifrequency Techniques

The multifrequency eddy current technique involves simultaneous excitation of the test coil with a number of carefully selected frequencies. Since the response resulting from variables is different for each selected frequency, the technique can yield data for the formulation of independent simultaneous equations which may be solved for the variables of interest. Thus, the technique provides a means for separating signals from noise and separately identifying various material conditions. The development of this technique for a specific application requires theoretical and experimental investigation of the important variables in the test material. Once the technique has been established, it provides a reliable means of detecting and identifying defects such as seams, changes in chemistry, or dimensional variations. The unit may be adjusted to minimize sensitivity to inherent material variables and permit further enhancement of defect signals.

Magnetic Reaction Analyzer

The magnetic reaction analyzer uses Hall elements (solid state field detectors) to measure the magnitude of the reaction field and also its phase.[4] This unit provides another versatile tool for use in eddy current inspection.

Pulsed Eddy Current Techniques

The pulsed eddy current technique uses a pulse generator rather than a standard sinusoidal current source to produce a broader spectrum of frequencies. Through the use of appropriate signal processing techniques, the separable response of various frequencies to a given defect may be obtained and discrimination between material noise and real defect signals may be achieved.

Applications

Applications of eddy current include:

- Sorting of materials to assure proper composition, heat treatment, hardness, or dimensions.
- Detection of surface or near-surface defects during high-speed inspection of rod, bar, extruded tubing, and welded tubing or pipe.
- Measuring thicknesses of nonconducting coatings on metallic substrates.
- Measuring thicknesses of metallic sheet materials.
- Detection of cracks or corrosion inside holes and tubes.

Eddy current inspection is used widely for the inspection of:

- Rod, bar, and tube for the detection of lap, seams, radial cracks, and alloy and dimensional variations.
- Spherical materials, such as ball bearings, for alloy and dimensional variations, heat treatment, and cracks.
- Sheets and foils to determine thickness, electrical conductivity, and magnetic permeability.

Because eddy current inspection is largely a noncontact method, it is frequently employed as an on-line inspection method, often with automated accept/reject mechanisms.

On each Saturn V, eddy current techniques were applied to inspect over six miles of tubing.[5] A special device, the Permascope, was also used to measure the thickness of the ablative coating on the S-IVB stage.

In summary, eddy current inspection provides a versatile inspection tool. However, successful application of eddy current techniques depends heavily on sound engineering for each application.

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Glossary

coil impedance - The ratio of coil voltage to coil current. This impedance is affected by the material inside the coil, and is sometimes used to measure eddy current response.

differential sensing - A method of measuring eddy current response in which two probes are used to determine relative variations between two sections of material. These two sections may be two separate pieces of material (one a standard and the other the test material) or they may both be located in the test piece. A comparison of the response from these probes can be made to determine changes in material characteristics. The signals from these two probes are electrically subtracted to produce the response associated with a discontinuity.

discontinuity - Any interruption in the normal physical structure or configuration of a part, such as cracks, laps, seams, inclusions, or porosity. A discontinuity may or may not affect the usefulness of a part.

encircling coil - An eddy current probe where the field coil circumferentially surrounds the material under test.

field coil - The coil generating the magnetic field that produces eddy currents in the part being tested.

fill factor - The square of the ratio of the diameter of a part to the diameter of the encircling coil or encircling coils. The square of the ratio of the internal coil diameter to the bore diameter for internal probes. The fill factor is a measure of coupling between the coil and the test object.

internal coil - An eddy-current probe where the field coil is wound on a bobbin and has a cross-sectional configuration close to that of the internal bore or passage of the test object.

lift-off - Lift-off is a measure of the gap between the face of a surface probe and the surface of the material being inspected. It is a measure of the coupling between the probe and the material.

permeability - Permeability is a measure of the ability of a material to support a magnetic field. Permeability measurements are usually made in terms of relative permeability with free space assigned the value of unity.

probe - Probe is the term usually given to an eddy-current sensor designed for use on a surface. In a broader sense, the term may be used to describe any type of eddy current coil or sensor.

standard depth of penetration - The standard depth of penetration is defined as the depth at which the eddy current field has fallen to 1/e, or 36.8 percent, of its strength at the surface. In practice, it is generally used to define the depth of inspection.

surface probe - A surface probe is an eddy-current probe which is brought in contact with the surface of a material to inspect the material. The area of coverage of a surface probe is restricted to its immediate vicinity.

void - Void describes discontinuities in which there is a physical separation between opposite walls.

CHAPTER VIII

OTHER METHODS

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OTHER METHODS

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CHAPTER VIII

OTHER METHODS

Introduction

Recent advances in materials and fabrication techniques have resulted in many new testing problems. Several new nondestructive-testing techniques have been developed to meet these emerging needs. Some of the more promising of these new techniques are discussed in this chapter.

Thermal Methods

Thermal testing methods are being used to directly or indirectly measure the effect of a discontinuity on the heat-flow characteristics of the part being tested. Included are the use of infrared radiometry, cholesteric liquid crystals, and temperature-sensitive paints and coatings. All of these methods measure the surface temperature distribution in the object under test to determine the integrity of the underlaying structure.

Heat applied to the surface of a structure will diffuse uniformly into the structure unless a discontinuity is present. A laminar discontinuity affects the heat flow in the material and produces a surface "hot spot" whose presence can be detected.

Thermal tests can be categorized as active and passive. In a passive test, the heat which is generated during operation of the part being tested is measured to locate hot spots that indicate discontinuities. In active tests, heat is applied to the test object.

Advantages and Limitations

Advantages are:

- Wide area coverage because the surface temperature is viewed optically.
- Contact with the test surface is not generally required.
- Very rapid and suitable for production-line testing.

Limitations are:

- Test material must be thermally conductive.
- Defects must be oriented to provide a reasonable area normal to the direction of heat flow.
- Defect size must present a significant obstacle to heat flow.

- Defect must be relatively near the surface to be detected.

Thermal testing techniques are most useful for detecting near-surface delaminations in such materials as honeycomb and laminar composites.

Techniques for Thermal Testing

Three basic methods are used to measure heat distribution on a surface: (1) infrared radiometry, (2) liquid crystals, and (3) thermal paints.

Infrared Radiometry. Heated objects emit infrared radiation whose intensity increases with temperature. Detectors sensitive to radiant energy in the IR region are used to monitor surface temperature distribution. For very low emissivity materials (e.g., aluminum), the radiant energy emitted is too low to be accurately detected and analyzed. Special coatings can be applied to the surface of such materials to increase emissivity. These coatings are also used for test objects having a nonuniform surface emissivity. Heat is applied to the surface by use of a quartz or infrared heat lamp. Natural isolation between the heat source and the detector occurs due to a difference in wavelength.

Three major scanning techniques are used with infrared detection systems: (1) line scan, (2) C-scan, and (3) area scan. In line-scanning, the source and detector are both stationary; the test object is moved past the heat source and then past the detector to provide a brief period between the application of the heat and the measurement of temperature distribution. Usually, a strip chart recorder or a similar device is used to record the results. The line-scan technique is not widely used because of the restricted area of inspection.

A more practical technique is C-scan. A wider heat source is used to "paint" a strip of heat on the surface of the test object. The test surface is scanned as it passes the heat source using a mirror system which rotates and reflects the radiant energy to a stationary radiometer. The resultant printout gives a plan view of the test object.

Area scan is generally used with passive thermal methods. A mirror system scans across a plane in a raster pattern similar to that used in an ordinary television and reflects the radiant energy to a radiometer. Area-scan techniques are very useful for testing large surfaces.

Liquid Crystals. Cholesteric liquid crystals exhibit temperature-dependent optical properties. Depending on the material used, they undergo a color transition from red to blue with increasing temperature over a specific range. Collectively, these materials can be used from -40 C to 290 C. The incremental temperature change required for transition can be as low as 2 degrees. Pure cholesteryl benzoate, for example, exhibits its color transition between 146.6 and 180.6 C. Liquid crystals have a rapid response time that varies from 0.2 to 10 seconds. Spatial resolution is limited only by the crystal structure and may be as low as 0.02 millimeters.

The materials are applied to the test object. When heat is applied, the color pattern indicates the temperature distribution on the surface. Discontinuities block heat flow creating a disturbance in the regular color pattern.

Generally, cholesteric liquid crystals must be applied directly to the surface of the test object. However, some cholesteric materials have been encapsulated in plastic sheets in an attempt to overcome this objectionable feature.

Thermal Paints. Thermal paints undergo only one color transition (usually from white to another hue) and transition occurs at a fixed temperature. Thermal paint is applied to the test surface which is then heated until a color transition occurs. A defect causes the transition to occur first in the area of the discontinuity because of a more rapid buildup of heat in that area. Many thermal paints will remain in a given color state, if additional heat is not provided. Therefore, at the appearance of a defect indication, heat may be removed and photographic records may be made to obtain a permanent record of the test results.

Applications

Thermal testing methods are widely used to inspect laminates and honeycomb assemblies for the location of disbonds between adjoining layers or members. Primary applications have been associated with production- and maintenance-inspection of aerospace components.

A novel technique of infrared inspection has been developed for inspecting integrated circuit boards.[(1)*] The system combines an infrared detection system with a specially designed microscope system to detect "hot spots" in microminiature components and electrical connections.

One example of the production application of thermal paints was the inspection of the brazed joint between the thrust chamber tube and the exit ring of the F-1 rocket engine for the S-IC booster.[(2)] A thermal paint that changed from green to blue at 140 F was used to detect poor bonds.

Acoustic-Emission Tests

An acoustic emission is a relatively low-amplitude stress wave within a material that is caused by the release of energy by microstructural events. With appropriate monitoring, these stresses can be detected and correlated with the events that caused them. Emissions are caused by microstructural

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* Superscript numbers refer to References shown at the end of this Chapter.

changes during elastic and plastic deformation, by ductile and brittle fractures, and by crystalline phase transformations. Acoustic emissions have been reported in wood, glass, concrete, beryllium, fiber glass, metallic alloys, composites, honeycomb structures, and bonding adhesives. Acoustic emissions are thought to be extremely short-duration signals with a broad frequency spectrum. Audiofrequency transducers may be used to detect such emissions; however, to reduce the effects of airborne (or space) sounds, ultrasonic sensors are used. Although the causes of these emissions vary, they are usually associated with changes in the integrity of a material.

Normally, one or more ultrasonic transducers are used to inspect a subject structure. Through appropriate signal-processing techniques, emission events are recorded as they happen, and conclusions can be drawn from an analysis of the emission frequency and intensity. (Frequency refers to frequency of events, and not to frequency content of the individual wave.)

Advantages and Limitations

The advantages are:

- Large volume of test object is tested.
- Tests are passive and do not require scanning. Energy does not have to be introduced in a definite way to interact with the defect.
- Failure prediction before destruction of the part is often possible by monitoring the part during initial loading cycles and/or while in service.

The limitations are:

- Acoustic coupling is required between the transducer and test object.
- Sufficiently high-amplitude ambient noise may interfere with signal interpretation and may be difficult to eliminate.
- Good acoustic path must exist between the source and the sensors. Materials with poor acoustic transmission properties cannot be tested.

Techniques for Acoustic-Emission Testing

An acousto-electrical transducer is placed on the surface of the part with a suitable couplant to transmit sound from the part to the transducer. Stress waves produced within the material are picked up by the transducer, fed into a high-gain, low-noise preamplifier, and then processed using an appropriate signal-analysis method. Several methods for signal analysis are used including the measurement of: (1) count rate (N), (2) total counts (ΣN), and (3) energy per burst. These are frequently plotted as a function an independent variable, such as load, cycles of fatigue, temperature, or time. Correlations which have been developed through experimental analyses are used in evaluating the material.

Filters are used to eliminate ambient noise. Acoustic emissions are generally monitored between 100 and 300 KHz. Single transducers have been used to monitor acoustic emissions, but multiple transducers are usually used on large structures to triangulate the location of the emission source. Present methods in analyzing test results are essentially empirical as research continues to gain better understanding of the basic mechanisms involved.

Applications

Applications which show promise include: (1) comprehensive studies in fracture mechanics, (2) detection of incipient failure in critical components during service and during proof testing, (3) in-process monitoring of welded joints, (4) evaluation of adhesive bond strength, and (5) in-flight detection of fatigue-crack propagation.

In fracture mechanics studies, acoustic-emission signals have been correlated with crack propagation processes. Since comprehensive analysis of these emissions was originally proposed[3], the theory has been generalized to yield an expression for the total number of counts produced during loading of a crack from zero load:

$$\Sigma N = AK^m$$

where

ΣN is the total number of counts

A is a constant of proportionality, depending upon test frequency and object geometry

K is the stress intensity factor

m is a constant of the material under test.

Fracture propagation becomes unstable when K approaches K_c, the critical stress intensity factor.

Using information derived from fracture mechanics studies, acoustic-emission techniques are being applied to the in-service monitoring of pressure vessels and other structural components. When a propagating flaw becomes critical, a marked increase in the acoustic-emission count rate is observed as indicated in Figure VIII-1. Potentially, continuous monitoring can lead to the early detection of incipient catastrophic failure so repairs can be made before the failure occurs.

There has been extensive research on in-situ detection of weld defects based on the hypothesis that thermal stresses in a weldment, if sufficient to cause plastic deformation or cracking in the solidifying weld, would

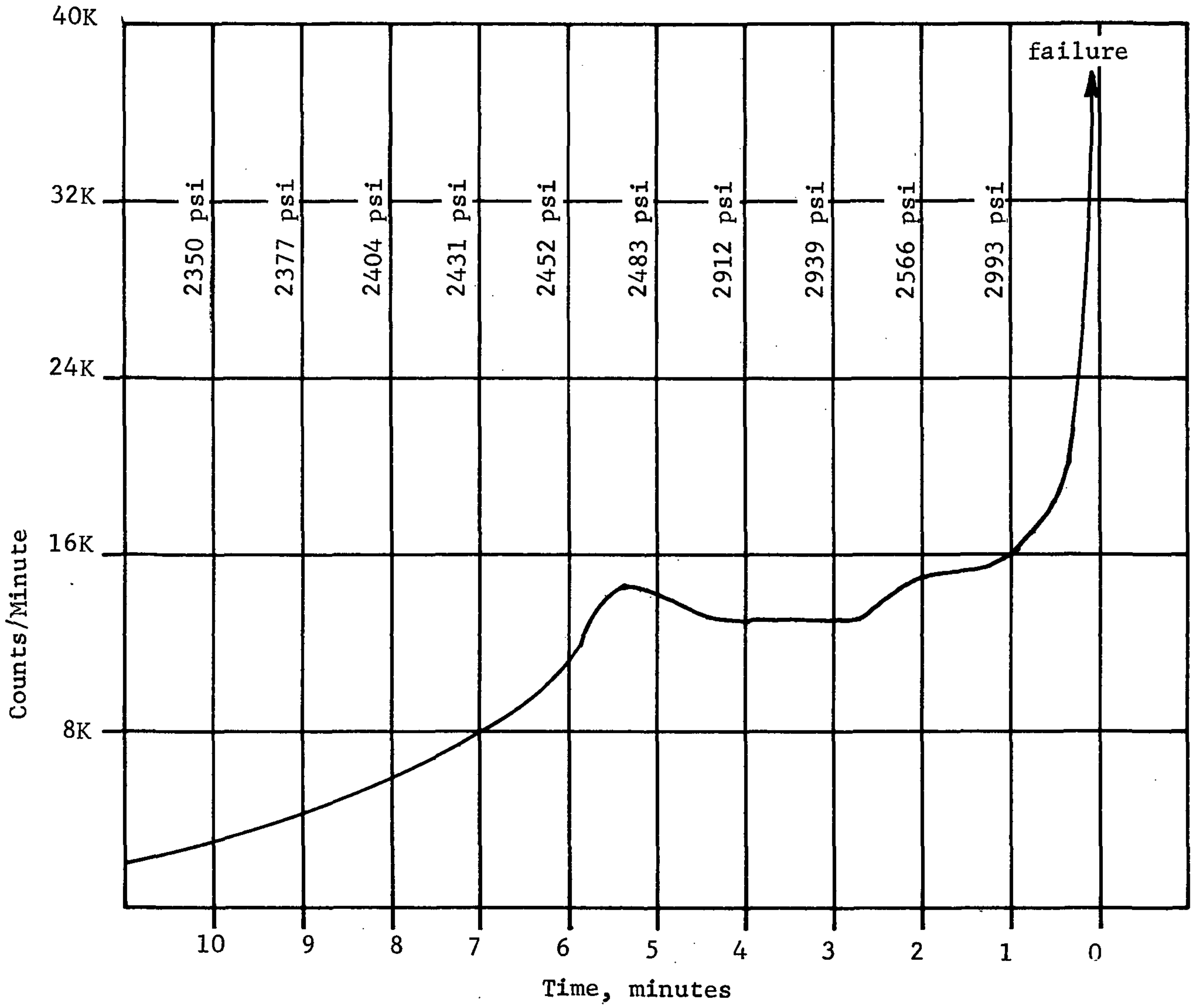

FIGURE VIII-1. ACOUSTIC EMISSION COUNT RATE CURVE FOR FINAL 10 MINUTES OF A HYDROSTATIC BURST TEST

(Tests were made on a 24-inch diameter by 1.6-inch wall thickness steel pipe.)

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generate acoustic emissions and provide a method for evaluating weld quality.[4] It has also been demonstrated that inclusions and pores as well as cracks can be detected by acoustic-emission techniques.

In evaluating these techniques for determining the strength of adhesive bonds, it has been shown that emissions peak when a bond is stressed to 90 percent of its ultimate bond strength.[5] This is one of the few techniques that permits nondestructive evaluation of bond strength.

The technique has also been studied to detect the fatigue of structural members in a small aircraft. It was concluded that it is feasible to develop an in-flight monitoring system "capable of detecting and locating emissions resulting from structural fatigue in aircraft".[6]

Holographic Interferometry

Holographic interferometry combines the principles of holographic imaging and classical Michelson interferometry techniques to provide a means of evaluating material integrity. Holography utilizes the coherent, monochromatic properties of laser light to produce a three-dimensional image of an object. A beam usually produced by a helium-neon laser is projected through a beam splitter which sends the coherent light through two different optical paths. One beam is used as a reference and is imaged through a set of lens-pinhole assemblies and mirrors onto the hologram plane. The second beam is reflected by the test object onto the hologram plane also. The resulting interference pattern at the hologram plane produces a diffraction-grating pattern on a high-resolution photographic plate. When viewed through the plate, a reconstructed image containing all the information observable in the original object is produced.

Advantages and Limitations

The advantages are:

- Coverage of large areas is provided in a single inspection.
- Defect indications are readily recognized because of an interruption in a regular fringe pattern.
- Relatively low operator skill is required once a system has been established and test parameters have been set. Establishment of the original system and parameters, however, usually requires the services of a highly competent engineer.
- Real-time analysis is possible.

The limitations are:

- Extremely stable surroundings are required; use of this system for production applications is difficult.
- Depth of field is limited by the coherence length of present lasers. Available power outputs presently limit the area of inspection. More powerful lasers are under development.
- Initial and operating costs are relatively high.

Techniques for Holographic Testing

Three principal techniques are used during testing: (1) real time, (2) double exposure, and (3) time average. In the real-time method, a hologram of the unstressed object is made. Then the object is stressed by application of force, heat, pressurization, or vibration. Fringes resulting from Michelson interferometry will be observed when the object is viewed through the hologram. This technique is capable of measuring very small surface displacements. The interference fringes are formed as a series of light and dark fringes representing 12 microinches displacement of the surface--one-half of the He-Ne laser wavelength. For a homogeneous, defect-free structure, the pattern of interference fringes observed should be regular. However, if the structure under test contains internal defects, the restribution of stresses produces anomalies in the observed interference patterns.

The double-exposure technique is similar. However, instead of viewing the object through the developed hologram, a double exposure is made. The first exposure is made with the object in its natural, unstressed state. An incremental force is then applied, and a second exposure is made on the same photographic plate. After development, the interference fringes are evident on the double-exposure holographic image. This method may be somewhat less sensitive than the method discussed above, because the viewer sees a static pattern rather than the dynamic movement of fringes in the real-time technique.

The time-average technique is used for obtaining data on vibrating surfaces. A hologram is exposed while the surface is being vibrated by, for example, an ultrasonic transducer. Surface displacements can be measured by counting the number of fringes on the holographic image. This technique also permits the identification of nodal and anti-nodal positions on vibrating structures.

Applications

Probably the best known and most widely used application of holographic testing is the inspection of honeycomb panels to reveal disbonds between the skin and the core.(7) The honeycomb structure is stressed by the application of a quick, but moderate, pulse of heat. The resultant differential expansion of the structural members produces a very low stress that is sufficient to produce a very high spatial frequency of fringes, 10 fringes or more per inch. Sometimes the honeycomb structure must be allowed to cool for a short period until the spatial frequency of fringes reduces to a level where flaw demarcations are readily evident. Other stressing methods include internal pressurization and vacuum stressing.

A few other applications include the detection of internal defects in turbine blades using a double-exposure technique[8]; the detection of separations between plys in aircraft tires[9], and the analysis of material behavior under service conditions.[10] Holography can be used to make quantitative measurements of the effects of material anomalies on the stress-strain and elastic-plastic behavior of actual components under various (including service) conditions.

Microwave Techniques

Microwave radiation occupies the electromagnetic spectrum between radio and infrared radiations (300 MHz to 300 GHz). This spectrum is used extensively for radar and telecommunications. However, microwaves have recently been used to evaluate materials. Microwaves penetrate most nonconductive dielectric materials; their reflection and scattering from boundaries and internal discontinuities makes it possible to detect defects such as disbonds, voids, inclusions and cracks.

Advantages and Limitations

Advantages are:

- Useful for the evaluation of non-metallic materials with poor acoustic transmission properties.
- Applicable to porous materials that are not easily tested by other NDT methods.
- Noncontact method.

Limitations are:

- Not applicable to metals or metallic structures, except for the measurement of surface properties.
- Considerable operator skill required (comparable to that required for ultrasonic testing).

Techniques for Microwave Testing

Three major techniques are used: (1) standing wave interferometry, (2) reflection measurement, and (3) detection of scattered microwaves.

Standing-wave interferometry is used primarily for thickness measurements. A standing wave whose phase and amplitude changes are well-defined functions of material thickness is established in the material being measured. The attainable resolution is dependent on frequency and the properties of the material. If thickness varies more than one-quarter of the wavelength, a dual-value solution can exist for a given reflected amplitude. However, for most applications, the nominal thickness of a material is known within ±1/8 wavelength. A change of 0.1 millimeter in the thickness of epoxy resin can be resolved using standing-wave interferometry.

Reflection techniques also employ a standing-wave principle with an amplitude-sensitive reflectometer sensing device. Since discontinuities within a material represent microwave boundaries, they cause a change in the amplitude of the reflected wave. The equipment is initially calibrated with a sample containing a known flaw and is adjusted to give a specific change in signal readout as the flaw is scanned. Figure VIII-2 illustrates the response of a calibrated microwave reflectometer to disbonds in a honeycomb and in a laminar composite. Sensitivity is dependent on test frequency and generally increases with frequency. As an example of achievable sensitivity, a 1-inch-diameter delamination was detected more than 2 feet deep in a solid rocket propellant.(11) However, extremely tight delaminations do not represent significant microwave boundaries, and therefore, cannot be detected.

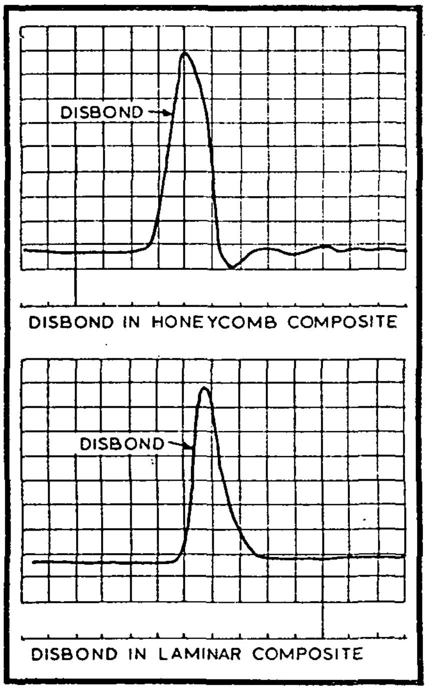

FIGURE VIII-2. MICROWAVE RESPONSE TO DISBONDS IN ADHESIVELY BONDED FIBER GLASS-RESIN COMPOSITES

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Figure VIII-3 illustrates the change in scattering cross section as a function of void size. At very long wavelengths, scattering varies linearly with the fourth power of the void diameter. As the wavelength approaches the dimensions of the void diameter, a peak response is observed at the beginning of the resonance region. As the void diameter becomes increasingly larger with respect to incident wavelength, an optical region is encountered in which the scattering is constant with respect to void diameter.

A sweep-frequency microwave generator has been used to create a microwave analogy to pulse-echo ultrasonic testing.(12) However, because of technical difficulties in producing "pulsed" microwaves, an alternate approach using broad bandwidth combined with frequency sweep has been developed to increase resolution. The detector sees both the sum and difference of the output pulse and the reflected microwaves. A phase-sensitive detector and display unit are used to monitor the results. This type of signal analysis and display allows the position of the reflecting interface to be determined within ±0.05 mm.

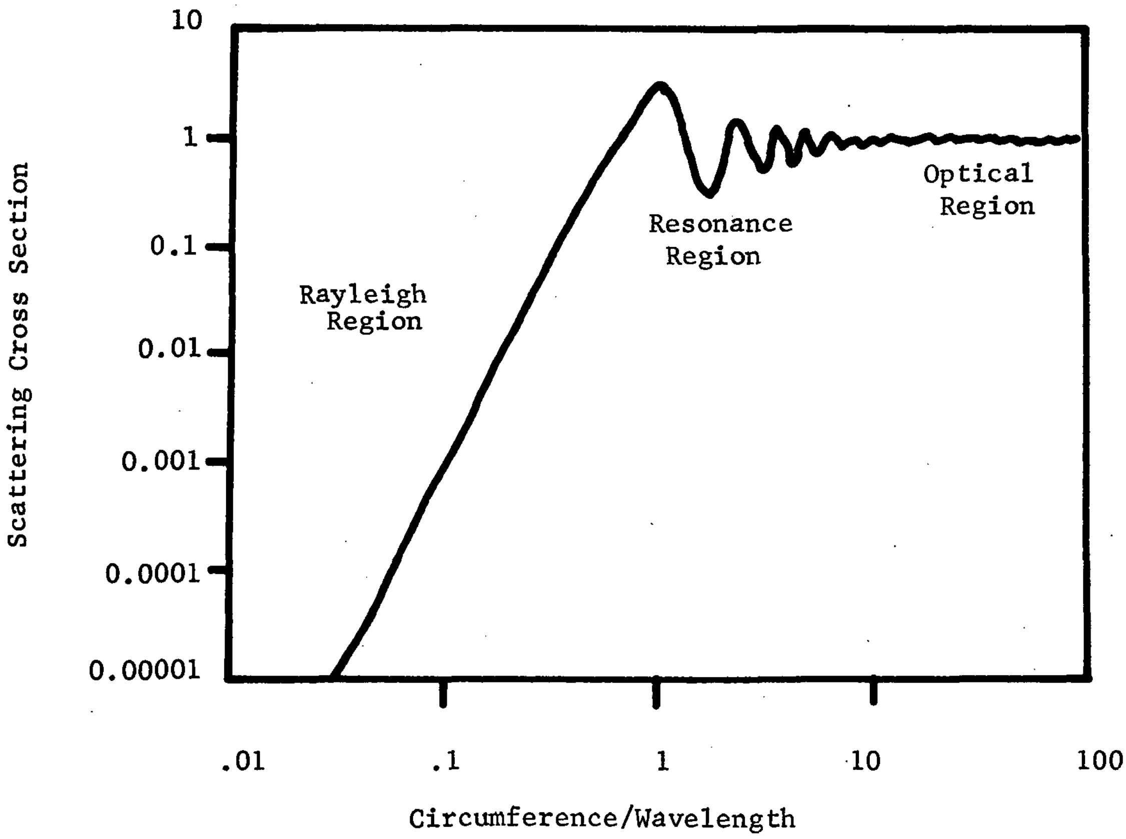

FIGURE VIII-3. MICROWAVE SCATTERING CROSS SECTION AS A FUNCTION OF FLAW SIZE

Applications

The measurement of thickness of dielectric materials is one of the simplest applications. Microwaves are also useful for the detection of voids, delaminations, macroporosity, and inclusions in non-conducting dielectric materials. These techniques have been used to detect disbonds in nonmetallic honeycomb, and in fiber-wound and laminar composites. The dielectric properties of a material can be measured, since they determine the propagation characteristics of microwaves within materials. In turn, these dielectric properties can be used to reflect other material conditions, such as degree of cure, oxidation, esterification, distillation, vulcanization, evaporation, and titration end points.

Microwave techniques have been used to determine moisture content, fiber orientation in composites, specific gravity, and degree of homogeneity. Some work has also been done on the measurement of glass-to-resin ratios in various composites. Metallic surfaces have been inspected for cracks, scratches, and other flaws that are as small as 100 microinches.(13) In addition to the primary advantage of being a noncontact method, microwave surface inspection is more universally applicable than other existing magnetic and optical methods.

Eddy-Sonic Test

The eddy-sonic test method was developed to overcome some of the problems associated with the use of couplants required for ultrasonic testing.(14) In an electrically conductive material, a mechanical force results from the flow of eddy currents. Since eddy-current fields are time-variant, the mechanical force is also time-variant and causes acoustic vibrations to propagate through the material.

Advantages and Limitations

The advantages are:

- Requires no couplant.
- Noncontact.

The limitations are:

- Applicable only to structures which possess an electrically conductive element.
- Instrumentation not yet readily available.

Techniques for Eddy-Sonic Testing

This method is usually used to locate disbonds in bonded honeycomb and laminar structures. An acoustic signal is generated in the electrically conductive portion of the structure, and the frequency of the exciting eddy currents is adjusted to produce a standing wave in a well-bonded portion of the structure. Any change in the integrity of the sample will result in a change in its resonant characteristics. Desirable test frequencies occur in the audio and near-audio range. In this range, induced vibrations may be air coupled to the acoustic pickup used for readout of the test results. Changes in resonant characteristics will be reflected in the output signal, thus permitting a poor bond to be detected. This technique may be automated, and probes have been built to scan the part with up to 1/8-inch lift-off distance.

Applications

Eddy-sonics have been used successfully on honeycomb materials with face sheets ranging from about 0.002 inch to at least 0.185 inch thick; core thicknesses have varied from 1/8 inch to more than 4-3/4 inches. Work thus far has shown that unbonds as small as 3/4 inch across can be detected, however, this is probably not the lower limit. This technique also has been used to detect core fractures and crushed core.

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