Part 4. Mechanized Scanning of Fluorescent Liquid Penetrant Indications

Advantages of Fluorescent Liquid Penetrant Test Systems

One of the most significant advances in nondestructive testing was the introduction of fluorescence in liquid penetrant testing. In this technique, the test object can be subjected to large quantities of excitation energy (generally near ultraviolet) with virtually no glare or highlights reflected from the part being inspected. Because of this, liquid penetrant indications containing very minute amounts of retained material may be readily seen and, therefore, very high sensitivity to small discontinuities is possible. Extraneous indications do develop from fluorescent material trapped in scale or on some rough spot etc. These are generally referred to as background. In many applications, the background level may limit the smallest size discontinuity that can be reliably detected.

Functions of Scanning Equipment for Liquid Penetrant Indications

The purpose of mechanized scanning of fluorescent liquid penetrant test indications is to automate the viewing and interpretation portions of the liquid penetrant test process. This is advantageous in obtaining reliable and reproducible results. The automatic scanning machine can theoretically be calibrated more accurately than the human, so simple *go/no-go* interpretations could be made more uniformly. Naturally, in addition to the above advantages, automated liquid penetrant testing potentially offers speed in inspecting large numbers of uniform parts that no human test operator can match.

Unfortunately, the potential has not been fulfilled. Scanning units in production applications have been too slow and less sensitive than a human operator and have had higher rates of false calls.

Ultraviolet Radiation Scanning Systems

Ultraviolet scanners consist essentially of (1) a source of ultraviolet radiation, (2) a photodetector sensitive to visible (converted) light but not to ultraviolet radiation and (3) the amplification and discrimination equipment necessary to interpret the signal produced. Generally, materials handling accessories will be required to move the parts to be inspected to and from the scanner, to index or move the parts under the scanner so that all desired areas are inspected uniformly and to mark or separate those parts rejected. Obviously, a system containing all the above functions would be very complex and may be expensive. It would also probably have to be specifically engineered for a particular part or group of similar parts, so it could be fairly inflexible. Two types of ultraviolet scanning equipment have been in comon usage in the late 1900's — the television scanner and the laser scanner. Each will be discussed separately here.

Television Scanner for Fluorescent Liquid Penetrant Test Indications

The television scanner illuminates the part with ordinary filtered ultraviolet radiation. A closed circuit television camera, equipped with a filter to remove the ultraviolet radiation, is used as the detector of the visible light test indications in this apparatus. The output video signal is then processed through a computer or other electronic equipment programmed to recognize the signals from rejectable anomalies. On receipt of a rejectable anomaly signal, the computer usually is programmed to initiate some rejection action such as marking the spot with paint for later disposal or sorting rejected parts into a rejection bin. Some pattern recognition and classification of anomalies are possible.

Laser Scanner for Fluorescent Liquid Penetrant Test Indications

The laser scanner uses a deep blue, violet or ultraviolet laser beam to illuminate the test parts. With this type of light source, a very narrow, very intense beam is produced. The scanning occurs as the beam passes over the part, illuminating only a very small area at any one time. The direction of the laser beam may be changed continuously by means of mirrors, the part may be moved under the beam or both may occur simultaneously. In any case, the level of fluorescence induced in the area covered by the beam is low unless the laser beam strikes a discontinuity indication, in which case a larger amount of fluorescent (visible) radiation is emitted. The fluorescence is detected by a simple phototube equipped with a filter to stop blue or ultraviolet radiation from the illumination source but permit the visible fluorescent light to pass. The signal takes the form of pulses that are then processed through a computer or other electronic equipment. A program to discriminate rejectable anomalies from background and initiate rejection action, is necessary. Pattern recognition and anomaly classification are possible.

Comparison of Laser and Television Scanning Systems

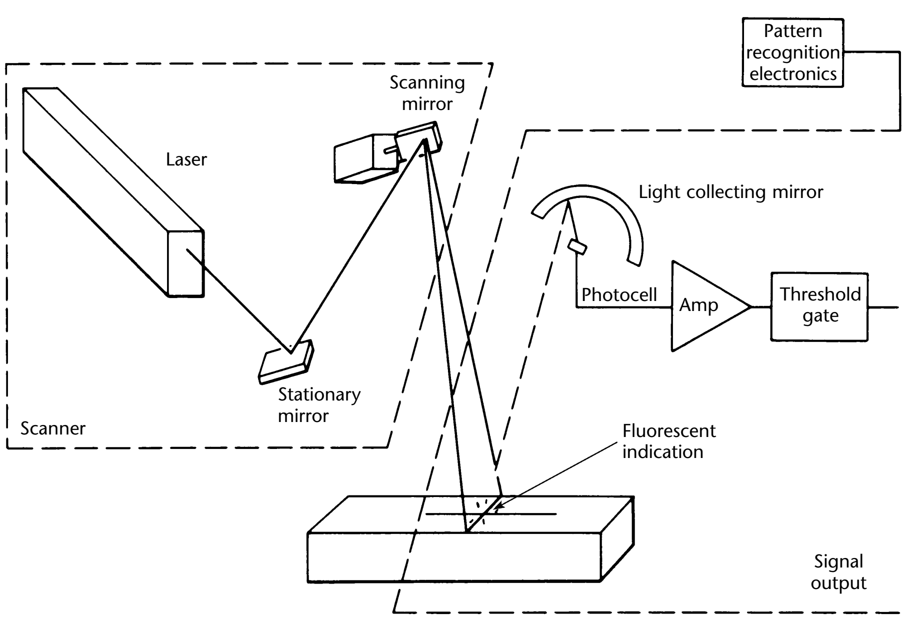
The laser scanner is the newer and better type of scanning system for the following reasons.

1. The laser beam provides much more intense excitation illumination in the area covered than an ordinary ultraviolet lamp, so the fluorescence excited is very bright and easily detected.
2. The detail discrimination is much better because a phototube can handle a larger contrast ratio than a television tube.
3. There are no depth of field problems because the fluorescent light is not imaged at any point. This makes part positioning much less critical than if an image must be formed.
4. The electronic circuitry required for the detector is much simpler and more troublefree than with a television system.

Flying Spot Laser Scanning of Fluorescent Liquid Penetrant Indications

A technique has been developed that uses a flying spot laser for detection of fluorescent liquid penetrant indications. As shown in Fig. 39, this system consists of three functional parts: a scanning laser, a photodetector and a data processor. The scanning laser causes a laser beam to move across the part to be inspected. When this exciting laser beam strikes fluorescent liquid penetrant materials retained in discontinuities open to the test object surface, a pulse of different wavelength light is generated. The photodetector converts this fluorescence pulse into an electrical signal. The data processor operates on these signals and

FIGURE 39. Functional components of flying spot laser scanning system for fluorescent liquid penetrant test indications.



determines if they represent discontinuities through pattern recognition techniques and signal intensity measurements.

The flying spot laser scanner with pattern recognition capabilities simulates a human operator for testing of fluorescent discontinuity indications in a large number of applications. The system has very large depth of field because system resolution is determined by the scanning beam cross section and not by large aperture optical imaging devices (as in the case of television devices). High density of excitation energy is available with a laser and extremely high sensitivity photodetectors will allow pickup of weak fluorescent liquid penetrant indications. The optical pattern recognition system simulates the human interpretation in that it recognizes shape and size for discontinuity determination and generally ignores background fluorescence effects.

Characteristics of Laser Beam

The scanner portion of the system contains a helium-cadmium (He-Cd) laser operating at a deep blue wavelength of 441.6 nm. The dyes and pigment used in fluorescent liquid penetrant testing materials will absorb blue as well as ultraviolet excitation and emit visible yellow light. Thus, a blue excitation source may be used rather than the familiar ultraviolet radiation. The blue has to be filtered out for visible interpretation, whereas ultraviolet is invisible. Photosensitive devices generally will detect both wavelengths so filters are required when either wavelength is used for automatic testing. The laser beam diameter is near 1 mm (0.04 in.) and the output power is nominally 15 mW. The laser beam divergence is very small, so generally no optical components are required. It is possible to use a lens or combination of lenses to reduce the beam diameter to a very small value and hence increase system resolution.

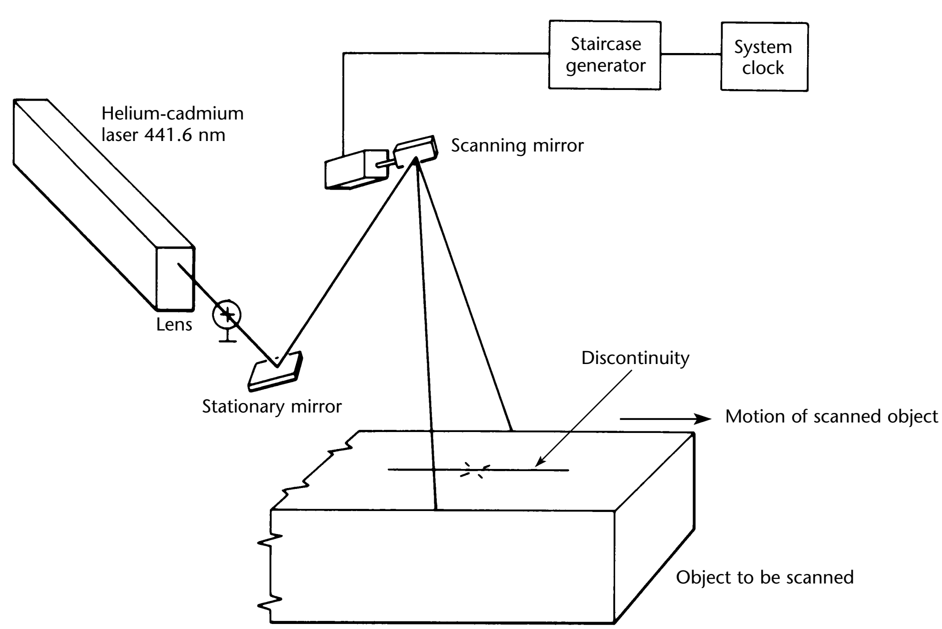
Laser Beam Scanning Motions

Figure 40 shows the arrangement of the components of the laser scanning system. The laser beam is directed to a scanning mirror that causes the beam to move back and forth across the test object and form, in effect, a line scan. The waveform used to drive the scanning mirror motor is a staircase function derived from the system clock. Thus, each position of the scanning mirror can be directly related to a given clock pulse. The scan waveform is adjusted as required. The scan motion is at right angles to the motion of the object being inspected so the entire surface is covered by the scanning beam.

Signal Detection and Analog Signal Processing

As the beam strikes the retained fluorescent material, it emits a pulse of yellow fluorescent light. Some of this light strikes the face of the photocell and is

FIGURE 40. Laser scanning arrangement for line scanning of test objects in motion.



converted into an electrical pulse signal. The amplitude of this pulse is directly related to the intensity of the pulse of yellow light. The phototube pulses are amplified and filtered and used to activate a threshold circuit. The threshold circuit output signal is a digital pulse used as input to the pattern recognition circuit.

These pulses may be used to generate a television image if desired, although this generally has no value in the automatic mode of operation. The beam position information plus the phototube analog output is all that is required for a television image. It is important to note that no optical lenses are used to generate this image. The image resolution depends on the beam cross section dimension. Therefore, the depth of field of the scanning system is very large because the laser beam has very small divergence.

Pattern Recognition of Fluorescent Liquid Penetrant Indications

Recognition of significant test indications is generally the most complex part of the automated scanning system. Pattern recognition is accomplished by one of three approaches: (1) an optical technique, (2) a hardwired digital process or (3) a microprocessor or digital computer.

Optical Pattern Recognition

In optical pattern recognition, a line shaped laser beam is oriented in the direction of the discontinuity (Fig. 41). This illustrates the formation of a line of light by use of anamorphic optics, that is, a cylinder lens that focuses the collimated light to a line parallel to the lens axis and maintains the beam's cross sectional width in the orthogonal direction because it does no focusing in that axis. A phototube detects and integrates the fluorescent flash that occurs when the exciting beam is coincided with the discontinuity. This is the simplest approach but it requires good parallel alignment of the beam and discontinuity and limits the system flexibility. A similar result can of course be obtained by laser beam scanning and electronically integrating the photocell output. This has the advantage of large depth of field but requires the more complex scanning arrangement. Figure 42 shows a laser scanning technique in which the line shaped laser beam illuminates the entire length of a parallel fluorescent indication of a linear discontinuity. Far less sensitivity would result if the beam and discontinuity were not parallel (Fig. 43). A

FIGURE 41. Optical pattern recognition of straight, linear fluorescent test indications.

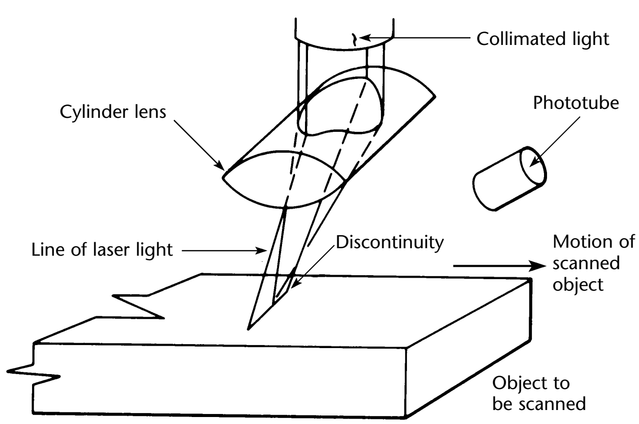


FIGURE 42. Example of test situation producing sharp electrical signal pulse from phototube detector: straight, linear fluorescent test indication is parallel to line focused scanning laser beam.

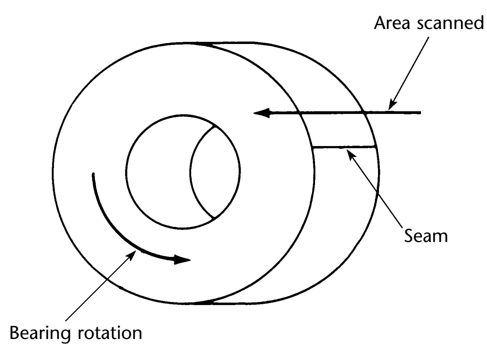
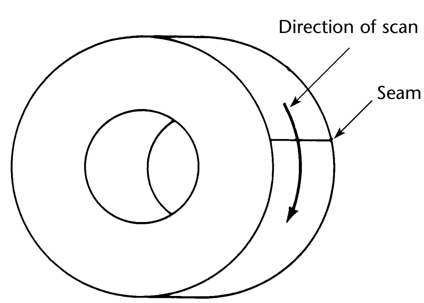


FIGURE 43. Example of test situation that produces reduced signal pulse levels from phototube detector when straight, linear test indication is perpendicular to line focused laser scanning beam.



parallel line of exciting radiation results in a form of optical integration of fluorescent light from the entire length of the indication. Similar slits of excitation illumination might conceivably permit optical pattern recognition for straight line fluorescent test indications in other orientations.

The background fluorescence usually consists mainly of the foggy yellow glow and a few isolated bright spots. In addition to this, indications that have many characteristics of discontinuities are frequently present. This includes indications caused by tool marks, scratches, thread crests and valleys, hole edges and others. A trained operator will ignore these and, if possible, so should the automatic system. This will increase the system complexity. In any case, most applications do require some sort of pattern recognition. This might range from the previous coincident light approach to a digital computer with pattern recognition algorithms programmed into its general operation.

Hardwired Digital Processor for Pattern Recognition

The hardwired digital processor for pattern recognition consists of multiple circuit boards, some consisting of several logic functions. The basic part of this portion is a large memory array; multiple bit elements are used. Each scan is adjusted for zone width. The input discontinuity signal is gated and fed into the array. The system clock pulses that were used to form the scanning waveform are also used as shift pulses and the discontinuity signals shift along in synchronism with the scanning beam. Auxiliary registers are arranged at the output of each array. These are grouped together to form a two-dimensional array.

Digital Computer Pattern Recognition

The digital computer signal pattern recognition technique is the most flexible because patterns can be changed by using different software programming. New programs are easy to input and output and may be continuously modified and improved as experience is gained. The software philosophy used is one of adjacent cell linking. If test indications (stored numbers in memory locations that are an analog of their location on the part) can be linked to adjacent indications, the probability is high that these are caused by discontinuities. The greater the number of links, the greater the discontinuity probability.

Flying Spot Fluorescent Liquid Penetrant Laser Scanning

The purpose of the flying spot laser system is to automate and speed detection of fluorescent indications and discontinuities. High volume testing of steel billets, roller bearings, welded pipe, automotive parts and the like is feasible. Inherently, the system minimizes the noise or confusion of surrounding indications and produces a discontinuity image that is more readily discernible.

The data processor operates on these signals and is programmed to determine through pattern recognition and intensities if a discontinuity has been detected. Automatic sorting and handling then takes over.

The advantages of human expertise in observation and interpretation are simulated through the system's attempts to recognize both shape and size in discontinuity determination while ignoring weaker signals from background indications. The computer can be programmed to recognize and act on different discontinuity patterns. The system has a large depth of field capability because resolution is determined by the scanning beam cross section and not by large aperture optical imaging devices, such as in television. In its broadest application, the system can be programmed to sort and assemble potentially discrepant indications and present them to the human operator for evaluation.

Although automated readout has been demonstrated to approach human capabilities in specific applications, the pattern recognition capability of the human operator exceeds that of automated readout systems. In addition, the false call rate of automated systems exceeds that of a human operator. Human intervention is necessary for critical applications.

References

1. ASTM E 1417, *Standard Practice for Liquid Penetrant Examination*. West Conshohocken, PA: American Society for Testing and Materials (1995).
2. Wald, G. "Alleged Effects of the Near Ultraviolet on Human Vision." *Journal of the Optical Society of America*. Vol. 42, No. 3. New York, NY: American Institute of Physics (March 1952): p 171-177.

8

CHAPTER

Comparators and Reference Panels

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PART 1. Cracked Metal Comparator Blocks

Simulating Cracks Found in Components

To conduct investigative programs on liquid penetrant tests, cracked test standards are needed. Panels containing networks of cracks of varying sizes are useful in establishing qualitatively the effect of liquid penetrant variables on general liquid penetrant effectiveness. A desirable characteristic of the cracks in cracked standards is that the size of the cracks be representative of cracks encountered in production parts or components. Of particular importance is the width of the cracks, because this dimension has an important effect on the ease with which a liquid penetrant enters the crack. During early experiments to artificially produce cracks simulating real process induced cracks, several production aircraft parts that had been rejected because of process induced cracks were examined to determine the width of the cracks. A summation of the crack widths in production aircraft parts is given in Table 1.

Various procedures have been tried to produce cracks that would be representative of process induced or service induced cracks. Some of those procedures applied to a variety of materials are described below.

Specimen with Low Cycle Fatigue Cracks

Concept of Fatigue Crack Specimens

To emulate small, tight fatigue cracks that might occur in gas turbine engine rotating parts, specimens have been manufactured with reduced fatigue cracks in each. High strength nickel and titanium alloys have been the materials of choice for these specimens because these are the materials used in the engines. The intent is not only to grow single cracks in each specimen but also to control the crack growth by using precise measurement techniques to gage the length of each crack after intervals of cyclically loading the specimen. Assuming a length-to-width aspect ratio of two to one leads to cracks with predictable depths. Thus, the performance of a liquid penetrant system can be precisely monitored.

One specialized application of this type of specimen has been the classification of liquid penetrant systems by the United States Air Force for inclusion in the qualified products list, QPL-AMS-2644.[1] For this application five specimens are used, each having a crack with a length in the range of 0.5 to 1.5 mm (0.02 to 0.06 in.). In this application, this type of specimen provides a source for a single unambiguous fluorescent liquid penetrant indication that could be analyzed. The set is processed according to standardized procedures specified in AMS 2644.[2] The luminance of each fluorescent indication is measured with a photometer. The sum of the measured luminances is then compared to similar sums from a set of reference liquid penetrant systems that produce a linearly increasing range of luminance values for the crack set. The reference system that produces the lowest sum produces no indication from the smallest crack.

It should be pointed out that even though indication luminance is used in this application to assign sensitivity classifications to liquid penetrant systems, luminance is not an absolute measure of system sensitivity. As discussed elsewhere in this volume, lack of control of the liquid penetrant processing variables, not the least of which is precleaning, can produce variations in brightness that do not correlate with the ability of a liquid penetrant system to indicate a small crack.

TABLE 1. Width of process induced cracks in production parts.

Material	Crack Origin	Crack Width µm	Crack Width (in.)
Titanium	forming cracks	7[a]	(0.0003)[a]
	unknown	17[b]	(0.0007)[b]
Aluminum	forging laps	2 to 50[a]	(0.0001 to 0.002)[a]
	unknown	20 to 90[b]	(0.0008 to 0.0035)[b]
Stainless Steel	welding defects	2[a]	(0.00008)[a]

a. Measured metallographically after cross sectioning.
b. Measured directly with electron microscope without cross sectioning.

Manufacturing of Low Cycle Fatigue Specimen[3-6]

The specimen material can be rolled or forged. In the former case, annealing is recommended to eliminate residual surface stresses. The approximate size of each specimen, 150 × 25 × 6 mm (6.0 × 1.0 × 0.25 in.), was chosen for convenience in manufacturing and liquid penetrant testing. However, the size of each specimen set should be uniform. One side of each specimen is arbitrarily chosen as the face in which a fatigue crack will be grown. The center section of this surface is smoothed by sanding followed by polishing with aluminum oxide powder with 3 µm (1.2×10^{-4} in.) particle diameter. The edges along the 150 mm (6.0 in.) dimension are slightly rounded to eliminate stress points that could result in undesired crack initiation during fatigue loading.

Various methods have been used to initiate fatigue cracks, including electrical discharge machined slots, mechanical notches in various forms and spot welds (thermal cracks). Spot welding has been used in some studies to produce a stress riser to initiate crack growth. Spot welds are easy to produce and almost always result in the initiation of a crack. However, extreme care must be taken to avoid multiple initiation or branching. Through experimentation, a heat and time setting for the welding equipment is found that will produce an area of damage about 2.5 mm (0.1 in.) in diameter. This damage consists of an area of recast metal and the surrounding heat affected zone. With this degree of damage, fatigue cracks have been found to initiate and grow in titanium (Ti-6Al-4V) to a detectable size after 20 000 to 50 000 cycles.

Typically these low cycle fatigue cracks are generated at room temperature using a load frame fitted with a three point bending fixture. A computer controlled servo hydraulic system is used to generate sine wave cyclic loading. In one setup a ratio $R = \sigma_{min}/\sigma_{max} = 0.1$ (where σ = stress) has been used with the maximum load set to produce a bending stress of approximately 80 percent of the material yield stress. For tight fatigue cracks, a stress level below 70 percent has been recommended.

During fatigue loading the crack starter defect is monitored with a microscope. Once a crack is detected, the length is carefully monitored in place or with a separate microscope. The measurements can be more accurate if they are made under bending stress to open the cracks. If the crack length falls within the target range, loading is discontinued and the cracked surface is machined to remove the crack initiation damage site. After final machining, the crack is stressed open again and measured to determine the final crack length. Additional machining can reduce the depth of the crack if desired. Final depth can be estimated from the originally assumed two-to-one length-to-depth ratio and the amount of material removed during machining. A light etch may be necessary after machining, even if the specimen has been stressed to open the crack for measurement. Etching is always recommended for panels to be used for liquid penetrant testing.

Occasionally two cracks will initiate. This may not be a problem if their included length is within the target range because they will eventually join to produce a long shallow crack with a length-to-depth ratio greater than two-to-one. Such cracks can facilitate the evaluation of certain characteristics of liquid penetrant systems. For example, a water washable liquid penetrant system may not detect such a crack as well as a postemulsifiable system.

Disadvantages of Low Cycle Fatigue Crack Specimens

These specimens are relatively expensive to manufacture. Because they are generated in fatigue, they are very tight and therefore difficult to clean between repeated processing. Ultrasonic cleaning in chlorinated solvents has been successful but chlorinated solvents have fallen into disuse because of effects on the ozone layer.

As of 1999, fatigue cracks were the only test specimens that could be used to satisfy fracture critical requirements of the National Aeronautics and Space Administration, and were used to classify the sensitivity of fluorescent liquid penetrant in accordance with SAE AMS 2644.[2]

Quench Cracked Aluminum Comparator Blocks

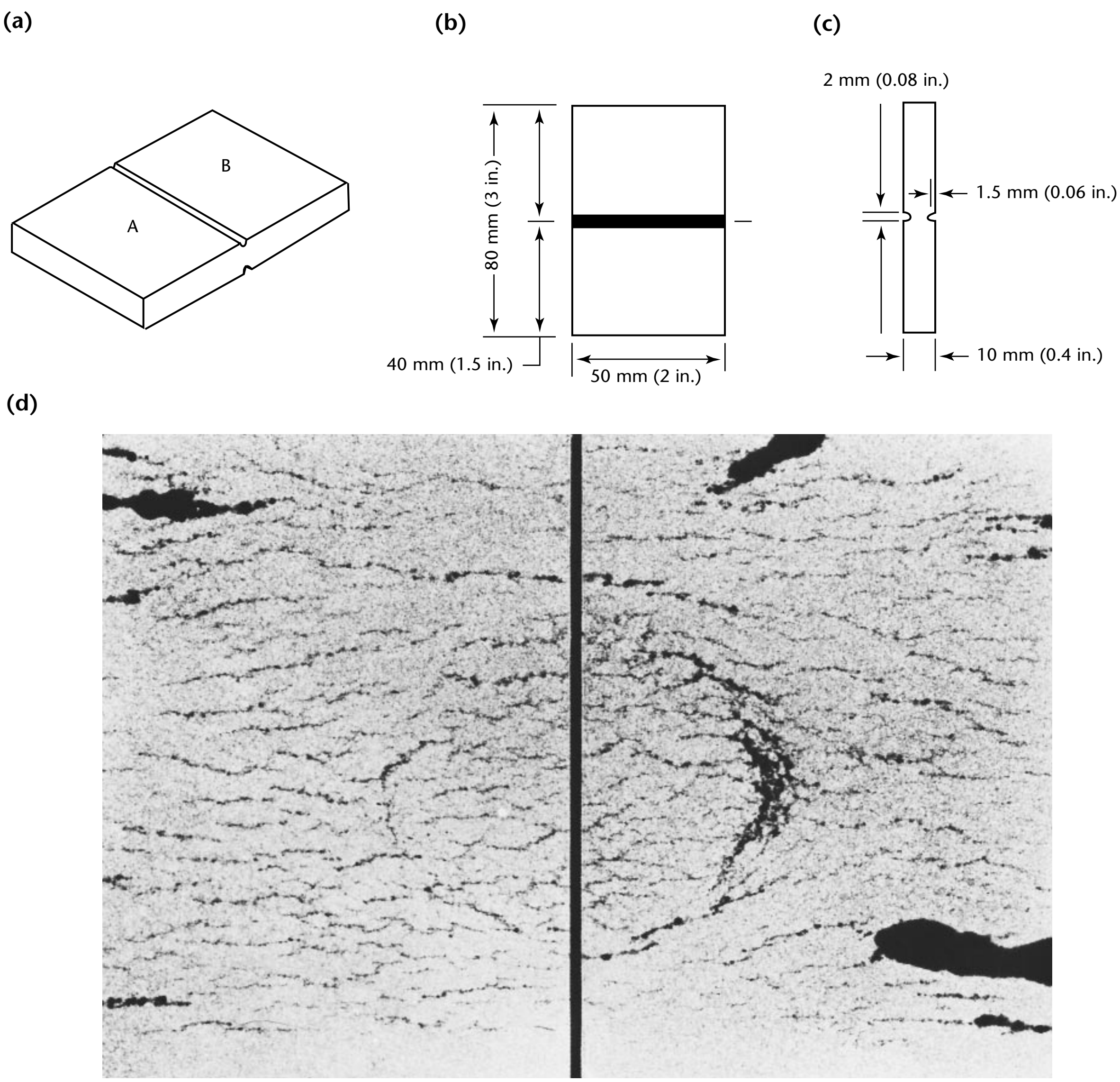
A tool that has been used to evaluate liquid penetrants and to judge the continued serviceability of a liquid penetrant testing system is the quench cracked aluminum comparator block. The cracked aluminum test block is described in both the *ASME Boiler and Pressure Vessel Code* (Part V, Article 6)[3] and in SAE AMS 2644.[2]

It is important to note that quench cracks rarely provide discrimination necessary for modern liquid penetrant materials and are not referenced in fracture control specifications. The following discussion of quench crack panels is included primarily for historical reference.

Preparation of Quench Cracked Aluminum Blocks

The liquid penetrant comparator panel (Fig. 1) is made from as-rolled 2024-T3 aluminum, as required in the applicable codes or specifications (for example, AMS 2644[2]), when smooth surfaces are desired. The grain direction of these panels is parallel to the largest dimension. To simulate surface roughness on test objects, a light surface machining operation may be used, if desired. Using a 510 °C (950 °F) temperature indicating material,[8] the panel is heated and then quenched in cold water. The temperature indicating material is applied in the exact center of the block in an area about 25 mm (1 in.) in diameter. A Bunsen burner flame is allowed to impinge on the underside. Quenching in cold water to induce cracking takes place immediately on full and complete color change of the temperature indicating material. Often, several repeat heating and quenching operations on the same block are needed to produce adequate crack patterns. A groove is then machined across the center

FIGURE 1. Cracked aluminum penetrant comparator block: (a) schematic; (b) planar view; (c) cross section; (d) photograph of liquid penetrant processed cracked aluminum block, sometimes referred to as liqiud penetrant comparator, used to compare performance of two different visible dye liquid penetrant processes. Dimensions are for guidance only and are not critical.



of each face of the panel, dividing it into two 50 × 40 mm (2.0 × 1.5 in.) sections (see Fig. 2).

A distinguishing identification mark should be inscribed on each section of the block to act as a reference for later determination of which material or technique was applied to different sections. A pencil mark is not satisfactory for this identification because it will usually be removed during processing. If it is a production practice to use acid or alkaline etching of parts before liquid penetrant testing to remove corrosion products, then cracked aluminum alloy blocks should be similarly etched for valid results.

Procedures for Cracked Aluminum Liquid Penetrant Comparator Block

In use, test liquid penetrant is placed on one section and standard liquid penetrant on the other section of the cracked aluminum block. The groove separates the two test sections. After liquid penetrant dwell, removal and developing, following established procedures, the two sections are usually compared for completeness of discontinuity patterns, sharpness of discontinuity delineation, color, general visibility and similar characteristics of interest. Either or both faces of the cracked aluminum panel may be used, as both top and bottom sides will have crack patterns. See elsewhere in this volume on the care and use of these panels.

Interference between Different Liquid Penetrants on Cracked Comparator Block

Two different liquid penetrants, coated on the separate sections of the cracked aluminum panel but still adjacent to each other, have an effect on each other even though the sections are separated by the groove. If the difference in surface tension of the liquid penetrant liquids is extreme, the liquid penetrant with higher surface tension is repelled from the center toward the outer edge of the panel. The other liquid penetrant with lower surface tension may cross the groove during the dwell period. Liquids that affect each other in this way should be compared on a panel cut into two separate sections, not merely divided with a groove. The sections should be well separated during the liquid penetrant dwell. Cutting the panel into sections facilitates the different processing techniques, such as different cleaning techniques or different developing agents. If high temperature or low temperature performance of a liquid penetrant is to be compared to performance of a standard liquid penetrant at ambient temperature, it is almost essential for the panel to be cut into two separate sections (see Figs. 2 to 4).

Figure 2. Aluminum block, cracked by heating and quenching, demonstrates performance of water washable fluorescent liquid penetrant without developer.

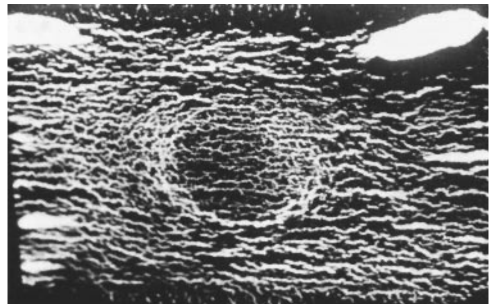


Figure 3. When comparing liquid penetrant performance at different temperatures, the liquid penetrant comparator is cut into equivalent sections for processing. This photograph illustrates two fluorescent liquid penetrant systems, one at 177 °C (350 °F), left, and the other at 27 °C (80 °F), right.

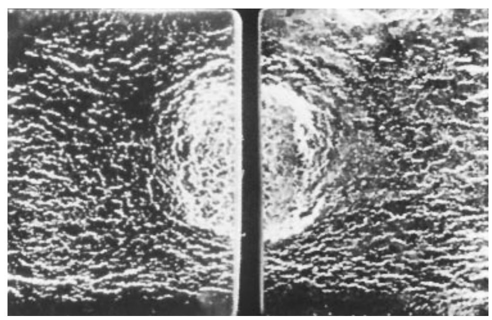


Figure 4. Liquid penetrant comparator divided into two separate equivalent sections to compare performance of same visible dye liquid penetrant and nonaqueous developer at 121 °C (250 °F), left, and 27 °C (80 °F), right.