SERIAL NO. **SSC-72**

SURVEY REPORT

(Project SR-127)

on

THE PRESENT STATUS OF NONDESTRUCTIVE TEST METHODS FOR INSPECTION OF WELDED JOINTS IN SHIP STRUCTURES

by

R. J. Krieger, S. A. Wenk, and R. C. McMaster

BATTELLE MEMORIAL INSTITUTE

(BuShips Project NS-011-067)

for

SHIP STRUCTURE COMMITTEE

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The Secretary of the Treasury

Member Agencies—Ship Structure Committee

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United States Coast Guard, Treasury Dept.
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Address Correspondence To:

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington 25, D. C.

SERIAL NO. **SSC-72**
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OCTOBER 5, 1953

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

October 5 1953

Dear Sir:

The Ship Structure Committee is undertaking an investigation entitled "Flaw Detection", the principal purpose of which is to foster the development of effective and economical nondestructive test methods for the detection of flaws in welded joints in ships' hulls. The first phase of this project has been a study of the flaw detection methods currently available or under development.

Enclosed herewith is a copy of the report on this evaluation, SSC-72, entitled "The Present Status of Nondestructive Test Methods of Inspection of Welded Joints in Ship Structures" by R. J. Kreiger, S. A. Wenk, and R. C. McMaster of the Battelle Memorial Institute.

Any questions, comments, criticism or other matters pertaining to the report should be addressed to the Secretary, Ship Structure Committee.

This report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

K. K. Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Enclosure

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BATTELLE MEMORIAL INSTITUTE

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for

<u>SHIP STRUCTURE COMMITTEE</u>

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SUMMARY

The nondestructive test methods applicable to flaw detection in welds in ship structures are radiography, magnetic particle, ultrasonics, and fluid penetrants. At present, radiography is the most extensively used. The magnetic-particle method has found considerable application, and fluid penetrants are used occasionally, while the ultrasonic method has not yet been used on ship structures.

Radiography, at present, is the most reliable and offers the best sensitivity to the detection of flaws in welds. The ultrasonic method offers a considerable potential and may prove more expedient than radiography if developed to provide the quality of inspection desired in welds in ship structures. The magnetic-particle method is established to the point where it serves as a useful inspection tool, particularly when used in conjunction with radiography. Further development may enhance its applicability.

Filmless techniques such as xeroradiography and fluoroscopy offer some potential, but both require further research and development before they may be applicable to this type of inspection.

INTRODUCTION

The field of nondestructive testing has grown to include a variety of methods[(1)*] having a wide scope of application. At least one or more of these methods are in use in nearly every manufacturing plant in the United States. The most extensive use of nondestructive testing is in industries which fabricate metal products. The detection and removal of discontinuities and flaws greatly improves the quality of welds, castings, and forgings. Nondestructive testing also aids process improvement because it tends to point out the inherent weaknesses of welding, casting, and forging.

A very important application of nondestructive testing in shipbuilding and repair is the detection of flaws in the hull structure. The largest percentage of brittle failures in ships have been associated with weld defects; hence, to insure quality in a hull, it is desirable to detect and repair all major flaws in the welded joints in the critical areas of the structure. For many years, detection of flaws in hull welds was considered impractical because of the great lineal footage of welding and the massive structure of a ship. However, in 1943, the Navy began requiring radiographic inspection for all welds in the pressure hulls of submarines. This not only proved to be beneficial but also proved practical enough, so

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*Numbers in parentheses refer to references listed on page 29.

that in 1945, the New York Shipbuilding Corporation, at Camden, and the Bethlehem Steel Corporation, Shipbuilding Division at Quincy, Massachusetts, at the request of the Navy, instituted radiographic inspection to insure good weld quality in critical areas in combatant vessels of a new welded design.[(2)] In October of 1945, the Navy made radiographic inspection in critical areas a requirement for all combatant vessels. In this connection, the Navy issued the following publication: "X-Ray Standards for Production and Repair Welds", (Navships No. 250-692-2) 1945, Navy Department, Bureau of Ships, Washington, D. C.

The purpose of this report is to discuss the applicability of existing nondestructive test methods to the detection of flaws in welded joints in ship structures, and to make recommendations for further research, designed to improve these methods for the above purpose.

NONDESTRUCTIVE TEST METHODS PRESENTLY USED FOR FLAW DETECTION IN FUSION WELDED JOINTS

Several factors enter into the problem of selecting a nondestructive test method for flaw detection in ship structures. These are applicability, sensitivity, reliability, cost and time, and inherent personnel hazards. The type of flaw being sought and its location and orientation with respect to the surface will impose limitations on the effectiveness of certain methods.

Applicability. The applicability of a method takes into consideration such factors as portability of the equipment, accessibility of the welded area, and the type of flaw being sought and its location and orientation with respect to the surface.

Sensitivity. The sensitivity of any nondestructive test method may be broadly defined as its ability to detect finite discontinuities or changes in density in a given material or test object. For example, radiography may detect discontinuities equivalent to 2 per cent or better of the total thickness of the object under inspection but will generally not detect microcracks or narrow discontinuities perpendicular to the beam of radiant energy. Ultrasonic methods may reveal changes in microstructure under certain conditions. The magnetic-particle method offers high sensitivity to surface defects but rather poor sensitivity to subsurface defects in welds.

Reliability. Reliability may be defined as the ability of a method to produce consistent results.

Cost and Time. The time required to detect flaws with any given method must be considered as an economic factor. This time may include the equipment-setup time, detection time, processing of films or other recordings, and interpretation. For example, at present the radiographic-film pick-up method is time-consuming. The development of the filmless techniques, such as fluoroscopy and xeroradiography, may effect a reduction in inspection time over the radiographic method.

Personnel Hazards. Other than the normal dangers encountered in handling electrical apparatus, nondestructive test equipment, aside from radiation types, has no special danger for the user. The hazards of X-ray and gamma-ray radiations are, of course, fairly well known. This often confines the use of such methods to periods when fabrication personnel are off duty and requires that special precautions be taken at all times to protect inspection and other personnel.

Portability of Equipment. This factor is quite important in ship-structure inspection where equipment must be moved to the area to be examined. It is often necessary to locate equipment in hard-to-get-to places. Lightweight, compact, and rugged equipment that can be moved easily by one man is an important consideration of inspection personnel.

Accessibility of the Welded Joint. The accessibility of the welded joint often limits or even determines the inspection method. Radiographic methods require free accessibility to both sides of the joint simultaneously. The magnetic-particle method may be applied from one side only. The ultrasonic method may also be applied from one side only. In new construction it is often possible to have accessibility to both sides of a joint, whereas in repair work it is frequently impossible to get to both sides.

Types of Flaws. The many types of weld cracks are commonly classified by visual appearance. Seam cracks, root cracks, centerline bead cracks, crater cracks, and fillet cracks are referred to as longitudinal cracks when occurring in the longitudinal direction of the weld. It is significant that these cracks may lie in a plane either parallel or perpendicular to the surface of the weld and may lie entirely below or may appear open to the surface. Cracks appearing in a plane perpendicular to the longitudinal axis of the weld are referred to as transverse cracks. This type of crack is usually small and often open to the surface. Cracks which do not seem to be particularly related to the direction of the weld but propagate in all directions are referred to as multidirectional cracks. Many of these cracks may be extremely fine hence difficult to detect by most methods.

Such defects as incomplete penetration, lack of fusion, and slag inclusions, are readily detected by radiography. The magnetic-particle method will indicate the presence but not the type of such defects, provided they are located near the surface.

Porosity, another common defect, can best be detected and identified by radiography.

It has been previously stated that there are many types of nondestructive tests. At present radiography, magnetic-particle, ultrasonic, and liquid penetrants appear to be applicable to flaw detection in ship structures. These methods offer various degrees of applicability; hence, two or more methods may be required for certain applications.

Radiography

The radiographic film method is at present the most widely used for flaw detection in ship structures. Radiography is the most reliable of the present applicable methods. Sensitivities attainable with radiographic methods will, however, usually not detect microscopic cracks. Such defects as slag inclusions, porosity, incomplete fusion, and lack of penetration are readily detected and consistently identified by radiography.

A 2 per cent sensitivity is considered the minimum acceptable with most radiographic methods. X-ray sources will in general give better sensitivities than gamma-ray sources. The per cent sensitivity is the ratio of the smallest thickness difference visible on the radiograph to the thickness of the material penetrated by the radiation. "Radiographic sensitivity" refers to the ability of a given technique to reveal discontinuities or changes in density present in the material being examined.

Portability is a desirable feature in equipment to be used for inspection of welded joints in hulls. The relative weight, the over-all dimensions, and ruggedness of the tube mounting are factors which either facilitate or make more difficult the use of X-ray equipment. The majority of the present-day so-called portable X-ray units are still too heavy for one man to move about easily, and many of these units do not possess the built-in ruggedness required for ship-structure inspection. Units of 150 to 250 kvp are considered to be the most suitable for the range of joint thicknesses commonly encountered in hull weld inspection.

Gamma-ray sources of radium and cobalt-60 offer much more portability than do X-ray units, and within certain material-thickness ranges will give equal sensitivity. Gamma-ray sources also have an added advantage in that no power supply or connecting electric lines or maintenance are needed. Iridium-192 is another possible radiation source, which is not in common use in this country but is being widely used in England. In penetrating quality or hardness the gamma-ray sources are equivalent to million-volt X-ray units, with the exception of iridium-192, which is approximately equivalent to 400-kvp X-rays in radiation quality. Thus iridium-192 should offer great possibility for ship-structure inspection. The intensity of radiation from conventional gamma-ray sources is much less than the intensity of X-rays; hence, gamma-ray sources require longer exposure times. Although gamma-ray sources may require several hours per exposure in comparison to the usual few minutes required with X-ray sources, the time difference can be reduced because of the decreased set-up time required and the use of several sources simultaneously.

Schwinn[3] has done outstanding work on comparing the sensitivities of several X-ray and gamma-ray sources. The results of his work, as reported in Graphs 9, 11, 13, and 14, are summarized in Table 1. This work represents a good comparison of the sensitivities attainable and the exposure times required for the sources used for plate thicknesses of 1, 2, 3, and 4 inches of steel. Of the X-ray sources tested, the 250-kvp X-ray is to be recommended for the 1-inch thickness range. Radium appears to be preferred over cobalt-60 in the 1-inch range on the basis of improved contrast, according to Schwinn's report.

Overexposure to X- and gamma-radiations can seriously affect the health of human beings. Thus, every reasonable precaution must be followed to safeguard operating and transient personnel against excessive exposure. Conventional gamma-radiation sources offer some advantage over X-rays, especially when used in the field, inasmuch as safety may be provided by roping off the exposure area to a radius of approximately 11 feet for a 200-mg and 20 feet for a 500-mg radium or equivalent source. In addition, the more intense X-rays will produce fairly intense scattered radiations which are dangerous because of the wide area that may be subjected to these scattered rays.

TABLE 1. COMPARISON OF RADIOGRAPHIC SENSITIVITY OF VARIOUS X-RAY AND GAMMA-RAY SOURCES

[Based on report of Schwinn(3)]

Type of Radiation Source	In. of Steel	Focal Distance, inches	Time	Sensitivity, per cent
250-kvp X-ray machine	1	36	3 min	1
	2	Not practical		
	3	Ditto		
	4	"		
400-kvp X-ray machine	1	36	2.5 min	1-1/4
	2	36	15 "	1
	3	Not practical		
	4	Ditto		
1000-kvp X-ray machine	1	120	2 min	1-1/2
	2	36	5/12 "	1-1/4
	3	36	2-1/2"	1
	4	60	8 "	3/4
2000-kvp X-ray machine	1	360	1-1/2 min	2
	2	36	7/12 "	1-1/2
	3	36	2 "	1
	4	60	2 "	3/4
Cobalt-60 (1/4 x 1/8) 480 mr/hr at 1 meter	1	36	3 hr	2
	2	36	9 "	2
	3	36	20 "	1
	4	36	48 "	1
Cobalt-60 (1/8 x 1/8) 250 mr/hr at 1 meter	1	36	7 hr	2
	2	36	15 "	2
	3	36	32 "	1
	4	36	74 "	1
Radium--200 mg	1	36	10-1/4 hr	2
	2	36	32 "	1-3/4
	3	36	80 "	1
	4	36	160 "	1

All exposures were made on Type A film with .080-in. lead filter.

All X-ray exposures shown in minutes, and all gamma exposures shown in hours.

Safety of personnel, both the inspectors and co-workers, may be insured by close adherence to the recommendations of American War Standard Z54.1-1946, "Safety Code for the Industrial Use of X-Rays", published by the American Standards Association.

Filmless radiographic techniques, such as fluoroscopy, xeroradiography, geiger tube, ionization gage, and image-tube pick-up methods, have at present found little application to weld inspection. At their present state of development, these methods do not consistently give the contrast and sensitivity required for hull weld inspection.

The most serious obstacle to high-sensitivity fluoroscopy is the large grain size of fluoroscopic screens. This gives poor definition to the image. Fluoroscopy cannot compete with film radiography where high sensitivity for detection of small defects is required. Fluoroscopy offers better sensitivity to thick sections than to thin sections. Under ideal conditions and in connection with lightweight alloys, an optimum sensitivity of 2 per cent may be obtained. However, future improvements in fluoroscopic sensitivity should extend its use to ferrous materials and more critical types of inspection.

Xeroradiography, an all-electric method of recording X-ray images, is presently under development. The speed and contrast sensitivity attainable with xeroradiography appear to be generally comparable to those obtained with commercial

X-ray films. Xeroradiography possesses the advantage of high-speed dry-image processing. The method is not far enough along in development at present to be made commercially available.

Ionization gages, geiger counters, and image tubes in general appear to have little to offer as improvements on present techniques. One exception has been the recent adaptation of an image-intensifying tube of the Coultman type to the intensification of fluoroscopic images. This technique is being used in medical radiography but so far has not been used for industrial inspection.

Magnetic-Particle Method

The magnetic-particle inspection method is quite reliable for locating discontinuities which have an opening to the surface. It is widely used for the location of surface cracks. However, the magnetic-particle method is not so reliable when attempting to locate subsurface defects. If a subsurface defect is fairly large and within a few tenths of an inch of the surface, it may be detected, though it is not always possible to distinguish the type of flaw or what its exact size and shape may be.

The sensitivity of the magnetic-particle method is affected by the strength of the magnetic field, the magnetic properties of the material under inspection, the type of magnetizing current used, and the indicating medium used. Another important factor affecting the sensitivity of the magnetic-particle method is the surface conditions of the material under inspection. For instance, particle patterns set up by the distorted flux field established by small cracks will be more easily seen on smooth, clean surfaces than on rough, dirty surfaces. Alternating current is recommended for detecting surface cracks because the skin effect creates a stronger magnetic field near the surface. Direct current, which gives a more uniform field distribution, is generally recommended for detecting surface and subsurface discontinuities; however, half-wave rectified alternating current is preferred for locating deep-seated subsurface defects. This current combines the advantages of surge characteristics due to the wave form with additional particle mobility due to the pulsations.

The magnetic-particle method offers an advantage of portability. The equipment for checking welded joints in hulls need not be complicated. All that is needed is a source of sufficient current with leads and prods. Storage batteries and welding generators have often been used as a current source for limited inspection. The magnetic-particle method is advantageous where only one side of the welded joint is accessible, which is often the case in repair work.

Where it can be applied, the magnetic-particle method offers a rapid method of inspection. On the hull of a vessel the prods can be moved rapidly from place to place along a welded joint by one man while another applies the powder and notes the indications. In this connection extreme caution should be taken when using prods to avoid arc craters in the material under inspection, in view of the fact that arc craters have been found to be prone to trigger brittle fracture in hull plate. Permanent records can be made by cellulose-tape transfers if desired. The magnetic-particle method requires no special safety practices other than those precautions ordinarily required with low-voltage electrical apparatus.

Ultrasonic Method

The ultrasonic method of flaw detection probably offers more undeveloped potential than any other nondestructive test method. So far with commercially available ultrasonic equipment, this method has not proven to be sufficiently reliable for the detection of flaws in welds. Some of this unreliability may, however, be attributed to the inability of operators or inherent limitations of the method to distinguish between flaw indications and indications that are generated by a sound weldment.

The ultrasonic method is extremely sensitive to acoustic impedance variations; in fact, in some cases normal variations in the material, such as grain boundaries and microporosity, generate such a degree of background noise that it may obscure the signal from a flaw whose amplitude is of the same magnitude as that from a boundary. Another limitation of the ultrasonic method is the inability of the operator to distinguish certain types of discontinuities or flaws. The orientation and configuration of a discontinuity or a flaw also have an influence on the indications obtainable with the method. The amplitude of the ultrasonic energy that is reflected from a boundary is highly dependent upon the boundary area which is normal to the longitudinal axis of the ultrasonic beam. Flaws that occur in welds are generally of random orientation and configuration. Thus the extent of a flaw may be large, but if only a small portion of its area is normal to the ultrasonic beam, the reflected signal level will be low. However, the method is capable of a high degree of sensitivity over a large thickness range. It has been used effectively for detecting flaws in steel from one-half inch up to, and over, twenty feet in thickness.

The ultrasonic method may be considered as highly portable and offers an advantage in that it does not require access to both sides of the welded joint. In the case of a butt weld, the ultrasonic beam is transmitted into the material at an angle and is propagated by angular reflection from the upper and lower surfaces until it impinges upon a boundary that is normal to the beam axis and is reflected back along the same path. In order that the noise level and energy loss be minimized, the reflecting surfaces by which the beam is propagated must be reasonably smooth. The introduction of the sound energy into the test piece is usually a problem and must be accomplished through a liquid couplant such as water or oil. The straight-beam method, in which the ultrasonic energy is transmitted into the test object perpendicular to the surface, is quite impractical for the inspection of welded joints. The use of this technique would require the entire bead surface to be ground flush and smooth in order to obtain good coupling. The direct-beam method is less applicable to thin than to relatively heavy section thicknesses. Furthermore, the usual orientation of weld defects is such as to make detection by the direct beam less promising than by the angle-beam method. The angle-beam technique is presently the most promising way of using the ultrasonic method for quantity weld inspection.

The ultrasonic method, at its present state of development, has been used to a limited extent to inspect welds in steel. The method is capable of detecting many types of flaws, depending upon the geometry and orientation of the flaw. However, the present design of the equipment does not lend the method to the detection of flaws in ship hull structures. A satisfactory simple means of coupling the sound energy into the hull must be found. Further research and development should overcome this handicap and allow the method to be adapted to such inspection applications as welds in hull structures.

Fluid Penetrants

The liquid penetrants, although limited to the detection of flaws open to the surface are simple to apply. There are several portable kits commercially available. The penetrants are safe to use and provide a quick method for checking surface conditions, provided cracks or defects are open to the surface and not plugged with scale, slag, or other foreign material and are not on the compression side of the member.

EXISTING NONDESTRUCTIVE TESTING PRACTICES IN SHIPBUILDING AND REPAIR

The Navy has required radiographic inspection on a spot-check basis for hull welds in all combatant vessels since 1945. The exception to spot-check inspection is submarine work where the requirements specify that every inch of pressure hull welding must be inspected by radiography or another competent nondestructive method. In Naval construction, the exact intersections and joints to be radiographed are specified by the naval architects.

The Maritime Administration does not specifically require nondestructive inspection of hull welds of ships built for the Administration. However, it is known that at least one shipyard, at its own choosing, performs the same amount of inspection on maritime vessels as on naval vessels. In addition, the inspectors of either the Maritime Administration or the American Bureau of Shipping may request the shipyard to perform such tests if they feel any reasonable doubt as to the integrity of a weld.

Purpose of Flaw Detection

The main purpose of nondestructive testing of welded joints in ship structures is the detection and ultimate elimination of all objectionable flaws which, if not removed, may potentially trigger a brittle fracture. Once it is established that a flaw exists, the problem then is to decide whether the flaw is severe enough to warrant correction. The responsibility for this decision is usually delegated to the shipyard welding engineer or chief inspector. The basis for a decision may stem from a comparison of the inspection results with established standards, if available, or appreciation of defects and their influence on service performance based on past experience. The possibility of a specific flaw, if not corrected, encouraging the initiation of failure in a structure must be considered in all cases. Consideration must also be given to the potential improvement in the quality of the welded joint to be derived from the corrective measures to justify their cost. At present there are very few engineering data available on which to base a comparison. Essentially, it is not definitely known just how dangerous any given defect may be if it is left in a welded joint in the critical hull area of a ship. Shipyard engineers would like to have more information regarding the effect of flaws on the service performance of welded joints. It is recognized that most of this knowledge must necessarily be learned through laboratory research and testing. However, it is felt that, once the effect of severity of flaws is determined, nondestructive test methods may be modified so that inspections can be carried out more rapidly and economically than at present.

A secondary purpose of nondestructive testing of ship structures may be predominantly psychological. Welders, knowing that their work is to be radiographed or inspected in some other manner, usually become more conscientious in their effort and will in all probability strive to improve the quality of their work. The full psychological value of nondestructive testing in the improvement of weld quality can be realized only if the welder is given the opportunity to see the inspection results of his work.

Methods

As has been previously mentioned in this report, the major portion of flaw detection in welded joints in ship structures is being performed by radiography with film pickup. The majority of X-ray units in use are in the 150-kvp to 250-kvp range. One typical unit is mounted on a jeep to facilitate its mobility. This is a 250-kvp unit with a 108-pound head containing the transformer and tube. Another unit in use consists of a 35-pound tube detached physically from the transformer but connected electircally with 50-foot sections of high-tension cables. A foreign unit, available in the United States and now being used in some shipyards, consists of a 180-pound head containing the transformer and tube. This is a 175-kvp unit, reported to be ruggedly constructed. A new 250-kvp unit with a 150-pound head containing the transformer and tube is now commercially available. This unit offers the choice of interchangeable tubes with 45- or 90-degree anodes. The 90-degree anode allows inspection around 360 degrees of a plane, which may offer an advantage for submarine hull inspection. This unit offers another advantage in that the kvp may be varied continuously from 27 to 250.

Gamma-ray sources are widely used in shipyard radiography. Radium capsules up to 500 milligrams are in use along with cobalt-60 sources. Radium capsules are obtained on a rental basis or purchased outright. Cobalt-60 sources are usually purchased outright.

In addition to radiography magnetic-particle inspection is used quite extensively. The excavation and repair of defects is guided materially by frequent checking with the magnetic-particle method. Magnetic-particle inspection is also frequently used where both sides of a welded joint are inaccessible to radiography. This is often the case in repair work. In heavy joints, it is common practice to inspect for flaws with the magnetic-particle method after each two or three weld beads are put in.

The ultrasonic method has been laboratory tested but has not found any service application to hull weld inspection as yet. A special ultrasonic device is now under development for the Bureau of Ships. This device contains two cathode-ray viewers, one to show a plan view and the other to show a cross-sectional view of the weld. The scanning device is mounted on a carriage designed to cling to a ship's hull magnetically and move along a weld joint at the rate of approximately 6 feet a minute. Two jets are used to supply a layer of water used as the couplant for transmitting energy to the metal and picking up the return signal.

<u>Standards</u>

The standards in use for nondestructive testing of welded joints in ship structures are: "X-Ray Standards for Production and Repair Welds" (Navships No. 250-692-2), 1945, Navy Department, Bureau of Ships, Washington, D. C.; Section III of these standards represents the minimum requirement for structural hull welding.

These radiographic standards, like all other radiographic standards, are not based on engineering data derived from physical tests or service performance. Radiographs of fairly high-quality welds showing a minimum of defects have been chosen for these standards. Standards have not yet been developed for magnetic-particle and ultrasonic methods.

A set of comparison radiographs for welds is being developed by ASTM Committee E-7. These standard comparison radiographs are not classified for any particular product. It is intended that the consumer and producer agree on the basis of selection which then becomes the acceptance standard.

The availability of a "Collection of Reference Radiographs of Welds" showing typical welding defects and different degrees of defect severity has been announced by the International Institute of Welding. The collection consists of 50 radiographs of arc welds in steel plate with thicknesses of 10 to 30 mm. The collection is built up into a card system designed for rapid sorting and may be had in normal transparent film copies or paper copies. The radiographs in this collection have been accepted by the members of Technical Commission V of the International Institute of Welding after a careful examination by specialists in the 19 countries represented in the Commission.

Inspection Practices

The quantity of welding currently being inspected in the hull of naval vessels amounts to about 15 per cent of the total footage of welded joint in a vessel. This inspection is performed in the critical areas of the hull as specified by naval architects, and major defects are excavated and repaired. This includes every weld intersection in critical locations, a 17-inch long randomly selected area in critical butt welds between intersections, and all top ends of vertical welds in the sheer strake. This practice gives rise to two schools of thought.

One school feels that this type of inspection amounts to considerably more than a spot check since it is performed in the critical areas and major defects are removed. Common practices are to remove only the major defects as indicated by radiography or other inspection results of the designated areas. Additional inspection in critical areas is performed when a defect appears to extend beyond the limits of the scope of the original inspection. There is a possibility that major defects still remain in the welded joints in the areas of the hull that are not inspected. However, the probability of an objectionable defect's remaining in these areas has been considerably reduced, and the possibility of a welding defect's triggering a brittle fracture in the structure is therefore also reduced.

The other school feels that improvement in hull welding is brought about mostly because of the psychological aspect of nondestructive inspection in improving the welder's performance. Some shipyard engineers feel that the introduction of nondestructive testing effected a great decrease in the number of flaws that existed in hull welds prior to the time of any inspection. One shipyard welding engineer has stated that such defects as slag inclusions, incomplete fusion, and lack of penetration have disappeared almost entirely since the inauguration of an organized inspection program. However, it must be understood that the mere presence of a radiographer about a ship under construction is not enough to cause the elimination of defects. As previously stated, the full psycological value of nondestructive testing can be realized only if the welder is given the opportunity to see the results of the inspection of his work. Furthermore, he must be correctly informed as to the nature of any defect and what he can do to avoid its repetition. This aspect of nondestructive testing is used quite effectively in training welders.

In fairness to the welder it should be emphasized that not all objectionable flaws in welded joints are the direct responsibility of the welder. Poor welds may be due to other factors, such as weld-joint design, quality of the base and filler metals, and finally the adequacy of shipfitting provided for the welder. None of these are under the welding operator's control.

CONCLUSIONS

The full value of nondestructive testing in shipbuilding is probably yet to be realized. An examination of the list of ships which suffered serious brittle failures in service indicates that these were built at a time when the welder's performance could be inspected only by visual methods with perhaps a limited amount of magnetic-particle inspection. In contrast, the writers are not aware of a single instance of a vessel built with the aid of nondestructive testing, even to the limited extent described above, which suffered a catastrophic brittle casualty.

In the shipyards where nondestructive testing is used quite extensively at present it seems to have become an essential part of the program of ship construction and repair. The question of how thorough an inspection should be made must yet be answered. The psychological influence will never entirely eliminate flaws. On the other hand, it is doubtful that 100 per cent inspection, i.e., inspection of every foot of welded joint in a ship, will ever be desirable or necessary. However, it is felt that some effort must be made to determine the types and magnitudes of flaws that will affect the service life of a vessel and that a nondestructive testing program must be designed to develop methods that will facilitate the detection of all objectionable flaws in the critical areas of a hull from both the time and the cost aspects.

It is felt that nondestructive testing of welds in merchant vessels is every bit as important as it is in naval vessels. Also, it is believed that failures can be effectively reduced with the aid of a sound nondestructive testing program. However, before such a program can be established, it would seem that certain recommendations should be carried out.

Probably as essential as improvements in methods and techniques is the expansion of the present research program aimed at gathering information to determine the effect of the type and extent of a given flaw on the structural properties or load-carrying abilities of welded joints. In addition to this, nondestructive test methods other than film radiography should be evaluated as to their capabilities to detect a given size and type of flaw known to influence structural performance. The results of such a program should help to determine how extensive a nondestructive testing program is necessary for ship structures and what methods and techniques are most suitable for the task.

RECOMMENDATIONS

The authors feel that specific recommendations suggesting further research and development are in order. These recommendations are based upon indications that improvement in techniques and methods of nondestructive flaw detection are highly possible.

(1) Improvement in existing radiographic methods.

(a) Encourage X-ray equipment manufacturers to develop lighter units that are highly portable and possess the rugged features required of equipment used in field inspection of ship structures. By reducing set-up and maintenance time, such equipment would allow a higher rate of inspection per unit.

(b) Establish a program to explore the potentialities of iridium-192 and other promising radioactive isotopes. An adequate source of supply of those isotopes found applicable must be established. Data must be secured to compare their quality with established radiation sources for the inspection of welds in various thicknesses of steel plate.

(c) Develop standards based on research and service data. These standards should clearly show the maximum size of each type of defect that may be allowed to remain in a weld without the probability of triggering a brittle fracture.

(2) Improvement of filmless techniques.

(a) Promote the development of fluoroscopy to yield better sensitivity for thinner sections. Study the applicability of the method to the inspection of welds in ship structures.

(b) Review developments in other filmless techniques, such as the "Picker-Polaroid-Land" Process and the Westinghouse "Fluorex" Process from time to time to determine if further research has made any of these methods applicable to weld inspection in ship structures.

(c) Investigate the applicability of xeroradiography for weld inspection in steel. Xeroradiography must be improved to consistently give the maximum sensitivity required for ship structure inspection. Further, the optimum radiation source must be established for this process.

(3) Investigation of Magnetic-Particle Method.

The magnetic-particle method should be thoroughly evaluated to determine its ability to consistently detect subsurface defects in welds of a given size, type, and location. Standards must be developed for this method.

(4) Improvement of the Ultrasonic Method.

Improvements and modifications must be made on equipment for the ultrasonic method before it can be adapted to weld inspection on ship structures. Further, the method must be fully evaluated to determine its reliability to detect given flaws in welds.

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