QUALITY CONTROL IN WELDING

BY

R. S. C. MEDHURST AND H. GIBBS

Introduction

Welding plays a vital part in marine engineering and the application of welding techniques have had a considerable influence on the design and manufacture of many machinery items with improvement in efficiency and reliability. Current requirements for pressure vessels and nuclear reactor plant would not be possible without welding, and in addition to production advantages, the repair potential of welding is considerable.

Typical applications to marine engineering and accrued advantages are:

(*i*) The modern boiler, with its higher steam pressures and temperatures is more compact and more efficient than former designs having riveted or forged pressure parts. Welding has reduced maintenance troubles arising from joint leakage, and welded casings with trunked combustion air in open type boiler rooms have improved habitability conditions.

(*ii*) Fabricated turbine casings, gearcases, condensers and other heat exchangers, engine frames and bedplates have allowed more flexibility in design and minimized the use of intricate and suspect castings.

(*iii*) Butt welded joints, welded flanges and branches, fabricated valves and manifolds in pipework systems have given more scope in design, and reduced weight and leakage troubles. The leakage of radio-active fluids is not permissible in nuclear systems and these can only be contained within an all-welded design.

(*iv*) The use of high temperature and corrosion resistant materials in gas turbines and other plant subjected to high temperature service is facilitated by welding.

Welding is of considerable economic value in making repairs to machinery items, often *in-situ*, and so avoiding the high cost and inconvenience of removal from the ship, prolonging the life of the component and reducing the time the ship is out of service for repairs. The reinforcement of worn bearing surfaces on propeller shafts avoids the premature scrapping of large and costly items. Welding repairs to castings avoids long term delivery replacements.

The operational requirements of many engineering components are such that every precaution must be taken in production to ensure that all welding is of the highest possible standard and consistent with Service conditions, hence the need for rigid quality control.

When failures occur in a welded structure, these invariably result from an adverse combination of conditions in which defective materials or joints, surface damage or fortuitous arc strikes, sharp changes in section or direction, fatigue or shock loading, embrittlement or corrosion have been significant.

Such failures can be avoided by paying close attention to design details, material specifications, imposing close control over fabrication, and instituting rigorous inspection of materials, procedures and fabrication.

The cost of such measures is amply repaid by minimum or no repair or replacement costs, reduced production time and cost of material, reduced maintenance and increased assurance of avoidance of failure.

QUALITY CONTROL

Quality control begins with the design of the item and only ends when it is satisfactorily installed and working in the ship or service. To ensure the eventual integrity of the product, numerous controls and inspections are necessary during production and although each may have a particular purpose they are not competitive but complementary. It is the combination of good design, welding procedure and inspection arising from close co-operation between designer, metallurgist, welding and inspection personnel that ensures a satisfactory high-duty welded product.

High-duty fabrication should be based on the concept of producing consistently sound welds by preventing avoidable defects during production and not relying on post-weld inspection finding faults, with consequent repair or replacement action, achieving quality by repairing welded joints is a complete negation of quality control principles. There are three stages of inspection : before welding commences, during production, and after the work is complete. For the prevention of defects the first two phases are the most important, but it must be emphasized that although in principle non-destructive inspection only finds defects and does not prevent them, it does contribute to the quality in addition to proving its soundness on completion in that :

(*i*) The specifying of non-destructive inspection for a weldment tends to improve quality by psychological effect ;

(*ii*) Its findings can be used to improve procedures or enable corrective measures to be taken ;

(*iii*) Initial material proving and interim inspections are contributory to ultimate quality.

Experience indicates that product reliability is dependent on the following main considerations :—

(*a*) Basic design and choice of material
(*b*) Process and filler metal
(*c*) Welder and Procedure Qualification
(*d*) Adequate inspection.

Each of these groups contain a number of individual considerations which are subjects within themselves and beyond the scope of this paper, but the salient features of each are summarized below.

Design and Choice of Material

The designer is required to provide a feasible welding design and as much relevant information as possible should be shown on the production drawings. This necessitates a good general knowledge of welding, embracing metallurgy, design of joints, welding processes and procedures, and specifications. Important points with regard to welded designs are size and type of joint ; its location and relation to the parts being joined ; the avoidance of discontinuities and welded intersections, especially where cyclic conditions arise. The parts, welds and joints should be arranged as symmetrically as possible and the amount of weld metal kept to a minimum to help minimize distortion. It is of utmost importance that joints are fully accessible so that all runs can be deposited correctly and where possible, arrangements made for welding to be carried out in the down-hand position. Consideration should always be given to incorporating rolled sections and folded components into a welded structure.

When selecting the material for construction, full consideration must be given to its weldability and behaviour when welded, in addition to other factors such as mechanical properties, corrosion resistance, etc.; and in some cases this can be a deciding factor on its use. Weldability must be understood to mean that the results will function satisfactorily under the conditions of service.

The extensive use of mild steel for fabrications has familiarized most producers with the general requirements for making good welds in all thicknesses of this material, but repeat conditions cannot be optimistically applied to different materials. As the carbon and alloying content of a steel increases, the welding requirements become more complex and must be strictly adhered to for satisfactory results ; especially filler metal and heat treatment requirements. Preheat and interpass temperatures, where required, must be closely adhered to for the avoidance of cracking or fissuring. Much controversy exists with regard to post-weld heat treatment but in general the need for such treatment for reducing residual stresses is supported. Where applied, adherence to the stipulated time/temperature requirements, especially for local application, is essential otherwise more harm than good can result.

In addition to design for welding, consideration should also be given to design for inspection by appropriate non-destructive methods, particularly radiographic and ultrasonic flaw detection.

Process and Filler Metal

There are wide ranges of manual, semi-automatic and automatic welding processes available and careful consideration is necessary in selecting that most appropriate to the material and structure being fabricated. Many advantages can be obtained from the use of automatic welding when the circumstances are favourable, such as :

(*i*) Elimination or reduction of the personal element ;
(*ii*) Higher welding speeds and larger runs ;
(*iii*) Less distortion and good weld finish ;
(*iv*) Improved ' arcing factor ' due to reduction in ' off time ' for changing electrodes, etc.

The electrode, filler rod or wire is of vital importance because the strength of the joint largely depends on its composition and condition. To produce welds of the highest quality and efficiency, it is essential to use the correct electrode etc., in accordance with the proper procedure. The factors influencing the choice of filler metal are:

(*i*) The weldability of the material
(*ii*) The position in which the welding is to be carried out
(*iii*) The type of edge preparation
(*iv*) The strength and ductility of the deposited weld metal.

Mild steel electrodes are classified in accordance with their various welding characteristics to assist in selection for the purpose required (B.S.1719). The type and size of electrode must be carefully considered for each joint and not left to individual choice, particularly when special alloys are being welded. Defective welds can be produced by a good welder on a correct assembly if the electrodes are not of the appropriate gauge for the joint details, or are in bad condition; over-large electrodes hamper manipulation and cause lack of penetration ; small electrodes can result in cracks due to stresses set up in welding ; damp electrodes cause porosity, hydrogen formation and cracks. It is imperative that electrodes and other filler materials be kept clean, dry and undamaged at all times, particular attention being paid to storage conditions. Any particular requirements should be complied with before use, such as the baking of low hydrogen electrodes, and the manufacturers instructions regarding current conditions, etc., adhered to during use.

Where the mechanical properties are of utmost importance and in restrained joints where cracking can be a recurring problem, the use of low hydrogen type electrodes is advisable but operators must be familiar with their use.

Admiralty approved electrodes which have qualified by a range of appropriate tests are promulgated in A.F.O.s, but where requirements are not covered or in cases of doubt, advice should be sought before embarking on production.

Welder and Procedure Qualification

Appropriate qualification tests are necessary to determine the ability of the welder to make sound welds. Various requirements are laid down in Admiralty Specifications, British Standards and other codes of practice, but only welders who have passed the appropriate tests should be allowed to carry out production work of a required standard. It is essential that the welder maintains a consistent standard, and this can be assisted by regular employment on work of the appropriate standard, otherwise periodic qualification tests are necessary, which should also be applied where doubt arises as to the welder's work.

Procedure qualification tests are an essential requirement for all new projects undertaken by a manufacturer or contractor and their purpose is to establish the correct welding technique for the weldment and by mechanical testing prove its adaptability to service conditions. The time and effort spent on procedure tests before the commencement of production work are amply repaid in the avoidance of production difficulties and in the quality of the finished work.

The procedure test should, as far as practicable, simulate the production job and must be based on the actual parent material, its thickness, method of welding, joint geometry and any other particular requirements such as preheat and post-heat treatment. Mechanical and non-destructive tests prove the adequacy of the procedure to meet requirements and this procedure must then be closely adhered to during the production welding to ensure satisfactory results. Should a variable be introduced before or during production or for repeat work, then a new procedure should be established.

The information required from a procedure qualification test embraces parent material(s) ; details of joint preparation and its assembly ; dimensions of joints ; method and position of welding ; make, type and size of filler metal ; welding current or other applicable conditions ; number of runs and their arrangement in multi-run welds ; welding sequence (minimize distortion and locked-up stresses) requirements for preheating and post-heating ; mechanical and non-destructive testing requirements, and possibly the repair procedure. This information should be embodied on the approved production drawings, procedure charts or specification. A procedure specification must be a practical document that assists in completing the fabrication at minimum cost and to meet the service demanded. The correctly written procedure will help to eliminate mistakes by warning of them in advance.

Inspection

Visual inspection at all stages of production by a competent supervisor is of considerable importance in preventing defects or avoiding their development ; all other methods of inspection only detect defects.

Such inspection involves checking the suitability and condition of the welding equipment ; the parent material and filler materials ; joint preparation and fit-up, with particular attention to cleanliness and dryness ; checking the competency of the operator and his knowledge of requirements ; the provision of required mechanical test specimens.

Immediately prior to, and during welding, the supervisor should ensure that correct preheat and interpass temperatures are being maintained ; observe and if necessary correct technique and welding conditions ; inspect inter-runs for slag inclusions, slag traps, cracks, or any other features detrimental to achieving a sound weld ; and take the necessary action. In welds accessible from one side only i.e. pipe welds, care must be taken to ensure satisfactory root penetration before proceeding with further deposition ; and in double sided welds, care must be taken to see that the first runs are chipped back to sound metal before depositing sealing runs.

Visual examination of the completed weld prior to non-destructive testing by other methods can detect such faults as undercut, incorrect reinforcement, undersize fillet welds, and possibly more serious defects that can be corrected before applying radiography, etc. Sometimes many of the worst defects can be seen with the unaided eye and may outweigh small internal defects only discernable by more costly methods of non-destructive inspection. It must be emphasized that the root area of welds made from one side only have a predominant influence on the fatigue behaviour of welds, as do the external features of the weld contour, hence the great care necessary with regard to root runs in pipe welds, for which a number of techniques are now available to assist in obtaining good results, and the need to correctly contour or grind flush the external reinforcement.

The completed work should be checked for conformity with design dimensions or within the allowable limits of deviation.

It would appear from the foregoing that a supervisor, in order to obtain satisfactory work, would be required to be at the welder's elbow all the time. This of course is not generally possible or desirable. The duties mentioned are a general guide to inspection requirements and of necessity considerable trust must be placed in the qualified component welders, but the supervisor should know what is happening at all stages of the work and select stage points of inspection, knowing when to look and what to look for.

Specifications

Current Admiralty welding specifications covering engineering requirements are Chapter 5, 'Steel Pipework Fabrication' and Chapter 6, 'Metal Arc Welding' of the *General Requirements for Machinery* (*Engineering*).

These specifications have limitations in their applicability to the wide range of materials now in use for current construction and they must only be used for their specific purpose, i.e. pressure vessel and pipework fabrication in mild or low alloy steels (1 per cent chrome ½ per cent molybdenum).

For other materials the *A.S.M.E. Boiler and Pressure Vessel Code*, Section 9, or U.S.N. derivations from this are being used for welder and procedure qualification tests pending the formulation of suitable Admiralty specifications.

Consideration is now being given to relaxing heat treatment for mild steels and reducing non-destructive testing requirements consistent with good commercial practice.

Non-Destructive Inspection

Following metallurgical evaluation of materials, component design and mechanical tests on prototypes or samples, non-destruction inspection is used to ensure that subsequent production conforms to the specified requirements. Inspection methods differ according to the nature of the work, for example, welds in modern high-pressure steam systems require comprehensive inspection and proving tests to eliminate potential weaknesses due to material and/or human error.

Castings and forgings for certain applications may require inspection only in respect of dimensional accuracy and surface integrity. If, however, extensive machining is to be carried out, thorough inspection at an early stage of production may reveal unacceptable defects and result in considerable economy in cost and delay in obtaining replacements.

If extensive machining is required, more comprehensive inspection at an early stage is desirable to obviate rejection after machining with the consequent waste of machining effort, high cost and delay in obtaining replacements.

Where batch production is possible, critical inspection of prototypes can assist in establishing optimum production techniques and occassional sampling would meet subsequent needs.

Inspection Considerations

Considerable care is necessary when specifying inspection requirements to ensure adequacy and maintain a balanced quality control throughout a particular project; e.g. the application of techniques developed initially for high performance aircraft components may lead to an unnecessarily high rate of rejection (with inevitable increased cost) of components adequate for, say, the motor industry.

On the other hand, ignorance of available methods can lead to inflated costs and delay due to premature failure. Usually a compromise is possible based on :

(*a*) Service performance and effect of premature failure
(*b*) Production Schedules and cost
(*c*) Value of available inspection methods in relation to the work
(*d*) Inspection cost
(*e*) Field experience with similar components

It will be seen that the team work of design, overseeing and inspection groups is essential for satisfactory results.

Available Inspection Methods

Many specialised forms of inspection have been developed in recent years to meet specific needs (e.g. eddy current testing of non-ferrous tubes, gas leak detection, bond testing of bearings). For general application, four methods are in widespread use as follows :—

(*i*) *Aids to Visual Inspection* (*i.e. Surface*)

(*a*) *Ferrous materials*
Magnetic Particle Inspection in which the specimen is temporarily magnetized and surface discontinuities are outlined with coloured or fluorescent iron particles and made clearly visible to the human eye.

(*b*) *Non-Ferrous Materials*
Dye Penetrant Inspection in which a coloured or fluorescent liquid is applied to the specimen and drawn into discontinuities by capillary action. The surface is then cleaned and coated with a fine absorbent layer of powder. Dye remaining in the discontinuities is thereby drawn to the surface and clearly reveals the discontinuity. The sensitivity of (*b*) is appreciably less than (*a*) in relation to fine cracks.

(*ii*) *Inspection for Internal Defects*

(*a*) *Radiography*
Short wavelength electromagnetic radiation will penetrate opaque solids approximately in relation to the thickness, i.e. the shorter the wavelength, the greater the penetration. Changes of thickness can be recorded on photographic film resulting in a three-dimensional negative in which the film density is related to material thickness.

(*b*) *Ultrasonic Flaw Detection*
A development of marine echo sounding equipment in which sound vibrations in the range 0·5—10 Mc/s are introduced into a solid medium and reflected from internal and boundary interfaces. As the velocity of a given type of sound is constant for a given

material, time is related to distance (thickness). Unfortunately reflection amplitude may not relate to interface (defect) size due to orientation and distance from the transducer.

Limiting Factors of Inspection Methods

Many factors influence the choice of inspection methods and more than one method may be desirable for maximum information.

Detectors

When using either of the surface aids, components must be clean and for penetrants, thoroughly degreased. A thick layer of paint or sprayed coating will seriously reduce the effectiveness of magnetic particle inspection preventing direct contact between the magnet and the work and again between the discontinuity and iron particles. These methods of inspection may require assistance from Boroscope or Introscope type viewers for internal inspection.

Radiography

Radiography is now a well established inspection method for sub-surface defects. It is applicable to a wide range of materials and can, if properly applied, provide more information than any alternative single method. The following points should be borne in mind, however, when considering its use :—

(*i*) Flaw sensitivity is a percentage of material thickness and differs with differing types of defects in a given material, e.g. cracks are less readily detected than porosity and inclusions.

(*ii*) The fact that small changes of section in way of defects must be recorded, may preclude the use of radiography on specimens having changes of section.

(*iii*) A direct path is required through the specimen between X-ray source and film.

(*iv*) Equipment is bulky, fragile and expensive.

(*v*) Ionizing radiations are harmful and personnel require protection either by distance or screening.

(*vi*) Dark room facilities are necessary for film processing.

(*vii*) Interpretation of complicated radiographs requires a sound knowledge of the process and experience.

Ultrasonic Flaw Detection

Ultrasonic flaw detection is useful in a limited field of application but considerable care is needed to avoid misleading and inaccurate results. The following points have to be considered :—

(*a*) The range of materials to which application is at present successful is extremely limited. Results may be seriously affected by grain size and orientation.

(*b*) Transducers require reasonable uniform surface for application.

(*c*) The need for liquid couplant complicates vertical and overhead applications.

(*d*) The form of presentation precludes accurate diagnosis of defect type.

(*e*) Flaw sensitivity is approximately the converse of radiography i.e. most sensitive to cracks and least sensitive to porosity.

(*f*) Multiple flaws may mask each other.

(*g*) It does not distinguish between design notches and defects.

(*h*) It requires skilled and experienced operators.

The above limitations can be assessed and in many instances overcome by preliminary laboratory testing of facsimile components to establish satisfactory techniques before embarking on a new type of work.

From these remarks, it will be appreciated that, although useful, available inspection methods may be of limited value if used singly and complementary use is essential if maximum information is desired as is the case in many current nuclear components.

Current Applications

Fillet welds	—Magnetic particle inspection or dye penetrants
Butt welds up to 1 in. thick (Mild and low alloy steel)	—Radiography
Butt welds over 1 in. thick (Mild and low alloy steel)	—Radiography and ultrasonic
Butt welds in austenitic steel, etc.	—Radiography and dye penetrant
Tee butt welds (standing leg over $\frac{5}{8}$ in. thick)	—Ultrasonic and magnetic crack detection
Castings	—Radiography and appropriate surface inspection. Ultrasonic in some cases after limited rough machining.
Shafts, bolts, etc. (In service inspection)	—Ultrasonic and/or magnetic crack detection
Thickness measurement	—Methods include magnetic, gamma backscattering and ultrasonics
Bond testing	—Instrument developed for checking white-metal bearings after machining
Maring growth in pipes	—Radiographic method applicable to ships services
Riveted boilers	—Ultrasonic inspection to detect fatigue cracking at inside edge of riveted lap joints.

ADMIRALTY SERVICES

H.M. dockyards at home and abroad and certain W.P.S. organizations are each equipped with facilities to meet most requirements for radiography, magnetic crack detection and dye penetrants.

D.G.S., Bath, is similarly equipped with, in addition :

(*i*) Mobile radiographic units
(*ii*) Facilities for most forms of ultrasonic inspection, thickness measurement etc., either at Bath or on the site
(*iii*) A centralized office for interpretation of radiographs.

An X-ray laboratory is available at each home dockyard, Greenock and Bath. Consideration should be given to sending work to these laboratories in preference to work in contractors premises, with the following advantages :—

(*a*) The personnel protection problem is controlled
(*b*) Laboratories are better equipped than mobile units
(*c*) Cost mounts rapidly when staff is employed on detached duty
(*d*) A mobile X-ray unit comprises a 4-ton pantechnicon and most equipment failures occur during transit despite every possible care.

In this brief paper, it is only possible to deal with inspection in broad outline. Nothing supersedes careful visual inspection and at some stage even the most elaborate ‘ black boxes ’ revert to human vision for interpretation of the results. In the past twenty years, enormous emphasis has been placed on inspection applied to welds—to judge by films and reports received all too frequently, much of the emphasis should have been placed on the inspection of castings and efforts are now directed to this end.