WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, DECEMBER 1975

Sponsored by the American Welding Society and the Welding Research Council

R. W. Nichols

1975 Adams Lecture

The Uses of Welded Materials in Nuclear Power Engineering

Assurance of weldment reliability on the basis of "fitness for purpose" acceptance standards implies effective control at all stages of design, fabrication and operation in service

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He joined the Ministry of Supply in 1949 to study the effect of temperature on the properties of materials, transferring to the UKAEA Materials Laboratory at Clucheth in 1956, at first leading a team on the study of uranium and uranium ceramics materials. Since 1958 he has concentrated on the mechanical behavior of structural materials, including pressure vessel and pressure tube technology, welding, and nondestructive testing, and has been author or co-author of over 50 papers and 3 books on these topics, particularly including work on brittle fracture and creep.

He is currently editor of the ***International Journal on Pressure Vessels and Piping.*** *In 1969 he was Chairman of a UK Government Committee of Enquiry on Pressure Vessels and has since been Chairman of the British Standards Institute PV Research Committee and of the Institution of Mechanical Engineers PV Section. Other committee activities include chairmanship of the Management Board of the UK Certification Scheme for Welding Inspection Personnel, council member of the Institution of Metallurgists and of the Welding Institute Professional Board.*

Well known internationally, he is currently acting as Chairman of Commission X of the International Institute of Welding and is a Director of the International Congress of Fracture. In 1971 he received the degree of Doctor of Metallurgy from Sheffield University for work on the assessment of material for engineering applications. He delivered the President's Honor Lecture to the Non-Destructive Testing Society of Great Britain in 1972.

Lecture was presented at the 56th AWS Annual Meeting held in Cleveland, Ohio, during April 21-25, 1975.

ABSTRACT. The achievement of economic electric power relies greatly on all aspects of welding technology; in recent years the emphasis has been on the provision and assessment of weldments which will give reliable performance under service and fault conditions. The first stage is to choose materials and processes which in principle can achieve satisfactory results. Whilst manual and submerged arc processes are widely used, in some cases novel techniques have been developed, such as those for weld-formed elbows and pipe, multiple-strip and explosive cladding, tube to tubesheet welds and applications of friction welding.

The second stage is to develop detailed procedure specifications which will give the required result whilst minimising the risk of production of flaws. This had led to study of the causes of cracking where this had been found in practice. Hydrogen

Fig. 1 — Hand welding by GTAW process of inlet tail bends for AGR reheater unit (courtesy Babcock & Wilcox Operations Ltd)

cracking is now well understood, although background research is still providing information on which specifications can be based, e.g., with respect to drying and storage of electrodes. More recently reheat cracking and the associated underclad cracking has been a problem and research has indicated appropriate methods of assessment and recommendations for reducing the problem to acceptable levels.

The next stage in many cases is to provide automatic methods of weld process control which will ensure that the developed welding conditions are applied reproducibly. Techniques based on the refined control of normal welding variables have been applied to fuel element closure welds, heat exchanger tube and tube to tubesheet welds. Further developments in the use of total energy control for forge-arc stud welds and of back-face penetration control and front-face pool size control are described. Such procedures will help ensure reproducibility of weldment properties so that design can be based on laboratory and rig studies of the behaviour of typical welds. Such studies may involve not only conventional tensile properties, but also fatigue, creep and corrosion behaviour.

The possibility, even with rigorous control, of flaws remaining in the finished weldment has required the study of the significance of flaws on fitness for purpose and recent conclusions based on fracture mechanics assessments are outlined. The possibility of any such flaws growing under service conditions has led to the development of in-service inspection, mainly by the use of remotely operated, mechanical scanning ultrasonic inspection devices.

The use of such devices has implications on fabrication requirements and on the types of inspection to be used during fabrication. The search for reliability in inspection methods has included study of acoustic emission, acoustic and optical holography techniques. When flaws are found in operating plant it can become necessary to repair them using remotely operated welding techniques; typical cases are the repairs to pipes and bellows and the plugging of boiler tubes by explosive and friction welding. Throughout the paper examples will be provided drawn from UK experience and from other sources outside the United States.

Introduction

Nuclear power is playing an increasing role in providing the world with electrical energy. The ability to construct such plant depends in a major way on the application of welding technology. Over the years virtually every aspect of welding technology has been invoked in the design and development of economic nuclear plant, involving the provision of welding processes for new materials, the use of new processes and the execution of welds under difficult conditions. Recently however the nuclear welding engineers have devoted most of their attention to the problem of attaining and assessing weldments which would have an extremely high reliability in providing containment, pressure retention or protection from corrosive media.

In the early days of the application of welding, engineers relied largely on the final examination of the product to assess its potential reliability. More recently it has been appreciated that more than this is necessary and, in particular, detailed schemes have been applied for quality control and quality assurance applying at various stages throughout design and fabrication. It is not the purpose of this paper to discuss such schemes, but rather it will stress the need for every welding engineer to bear in mind this service reliability requirement throughout all of the stages in the life of the product.

There are various stages in the development of weldments which achieve this high reliability. First it is necessary to choose materials and processes which in principle can lead to the requirement weld with a low frequency of incidence of defects. In many cases this can be done by the well established processes of manual metal-arc or submerged arc welding. In other cases new processes have been developed or have allowed the use of more appropriate materials or of more economic designs.

One aspect of the choice of materials and processes for reliability is to reduce the risk of flaws such as cracks, an aspect which requires an understanding of the factors that may lead to the production of cracks during fabrication. This has led to work on the prevention of hydrogen cracking and of hot cracking, and more recently to intensive study of causes of cracking during reheating either by subsequent weld passes or by heat treatment, and to the study of cracking which has occurred under the cladding which is often applied to improve corrosion resistance in some nuclear plants.

Another aspect on which there has been considerable work in recent years is the assessment of weldments to establish their properties, both with respect to how these properties depend on process variables and with the aim of establishing better methods for measuring such properties in procedure tests. Work on implant tests, on brittle fracture and fatigue behaviour, on creep and corrosion resistance falls into this category.

The next stage is to take the particular process in its application to a particular welding problem, and optimise the conditions so the required properties of the weldment are achieved with the minimum occurrence of flaws. Once this has been done, process control must ensure that the welding procedures applied follow in precise detail those used in the procedure tests. In some cases, particularly those of a repetitive nature where consistency is an important requirement, this has been best achieved by application of automatic control of welding variables such as voltage, current, time, work or electrode movement, atmosphere purging. More recently attempts have been made to control the process by some aspect of the weldment as it is made — for example, the control of penetration by observation of the back of the weld or of the weld pool size.

Even so, it must be recognised that flaws in the weldment may still occur, and the complete elimination of such flaws could be both unnecessary and impracticable. Recent work has been aimed at establishing the effect of typical flaws on the fitness of the component to carry out its design purpose. Such work is leading to a better understanding of where repairs are essential and to a change in inspection philosophy for components where high reliability is recognised. The continuing search for methods of improving operational reliability has led to the development of in-service inspection techniques for applications where access and radioactivity problems necessitate remote operation. The use of such techniques has implications on the design and on various aspects of the fabrication process.

Finally, it must be recognised that in some cases flaws will be found in service which need to be repaired if operation is to continue. This has led to the development of repair techniques for remote application.

It is not possible in a paper of this length to review comprehensively each of these areas. Rather it will highlight recent developments by describing particular examples.

Welding Process Developments

For many of the weldments required in nuclear plant, well established welding techniques are appropriate. The use of submerged arc welds for main pressure vessel joints is commonplace, and in some situations manual methods are the most appropriate. Figure 1 shows hand GTA (gas tungsten-arc) welding of reheater inlet tail bends of one of the heat exchangers for an Advanced Gas Cooled Reactor. Orbital welding is often used for tube butt welds as shown in Fig. 2. In some cases the welding machines have to be adapted to cope with limited access; the example in Fig. 3 shows an orbital welding machine developed for a position with less than 25 mm between tubes, in which an integral 360 deg shield was provided concentric with the tungsten electrode.

The need for control of penetration and of the surface contour of such welds has led to the application of current pulsing which can average out the random fluctuations in stepped progression of the weld pool so giving a more consistent underbead profile. The selection of pulsing conditions involve the balance of achieving the required contour against the risk of worsening porosity or solidification cracking or of producing a surface rippling which can interfere with subsequent inspection (Ref. 1). Figure 4 shows the satisfactory weld profile (with concavity specified as less than 0.25 mm) that can be achieved in a GTA orbital weld on 1.8 mm thick mild steel tube using a current pulse with a sloping characteristic on trailing edge to reduce solidification rate and so the risk of solidification cracking. The weld head is stationary during pulsing except during the last pulse where an extended crater fill was desired.

The electroslag process has been used for particular components, particularly those which can be normalised before incorporation into the main assembly. A particular application of electroslag is as a remelting process in the production of dissimilar-metal transition joints with controlled composition gradient. Yapp and Bennett (Ref. 2) have described an electroslag process with a composite feedstock made up with, typically, the ferritic steel as its lower part and the austenitic steel as its upper part. The composition of the weld pool changes as more of the austenitic steel is melted into the weld pool, the composition change usually varying exponentially with position. Problems due to over-vigorous arcing in starting were overcome by using bundles of 10 to 15 wires each about 3 mm diam by 150 mm long of the same composition as the initial feed stock. After forging, such joints have shown good behaviour in stress rupture and in power station service simulation tests.

Fig. 2 — Use of orbital welding machine on AGR boiler feed tail assembly (courtesy Babcock & Wilcox Operations Ltd)

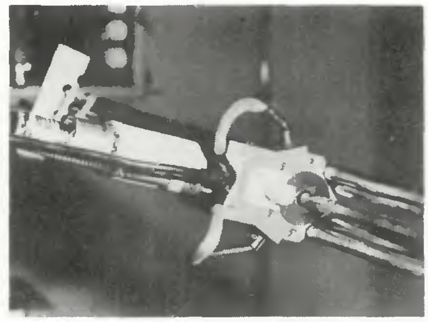

Fig. 3 — Orbital welding machine with 360 deg integral gas shield for limited access where tube spacing is less than 25 mm (Ref. 1)

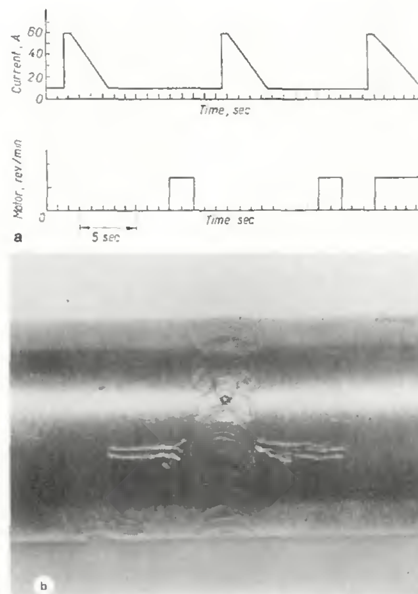

Fig. 4 — (a) Pulse slope and electrode index relationship in pulsed GTA tube/tube welding. Note: electrode is moving during slope down of last pulse (Ref. 1); (b) Pulsed GTA orbital weld on mild steel tube (14.5 mm OD 1.8 mm wall, showing satisfactory profile. Scribe mark indicates the 9 o'clock position)

The use of electroslag melting to produce weld-formed pipes and elbows, (Fig. 5(a), has been described by Sato (Ref. 3) and is to the stage where the Japan Welding Engineering Society now accept it for main nuclear coolant piping. It is claimed that its fine grain size, (Fig. 5(b), gives improved inspectability by ultrasonics and improved weldability because of homogenity and purity. Another novel use of electroslag welding described by Sato (Ref. 3) is to build up a stub on a tubesheet to overcome some of the problems in providing high reliability tube/tubesheet welds for sodium/water heat exchangers (Fig. 6).

Friction welding has been used to provide effective dissimilar metal joints in studs and in tubular transition joints. It has also been used for seal welding of tubes into tubesheets (Fig. 7). Explosive welding has been used for the production of clad plate (Ref. 4) and for some dissimilar metal joints and, as will be discussed later, for plugging of tubes.

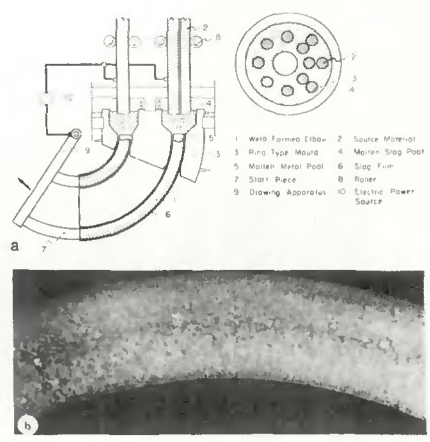

Fig. 5 — (a) Schematic diagram showing weld forming of austenitic pipe elbow (Ref. 3); (b) macrostructure of circumferential section of weld formed elbow (X 0.5, reduced 66%)

The Reduction of Cracking Problems

Whilst the underlying causes of hot cracking and of hydrogen cracking have been understood for some time, developments in detailed understanding and in assessment techniques continue to arise. For example, work at the Central Electricity Generating Board (CEGB) Marchwood Laboratory has emphasised that drying of basic-coated manual metal arc electrodes (2 Cr-Mo and mild steel) for 1 h at 150 C and storage at 90 C, as has been required by British Standards, is insufficient to keep electrode hydrogen levels below 10 ml/100 g of metal. Baking at 250 C for 1 h is necessary for this standard, whilst baking at 450 C for 1 h gives hydrogen levels of 5 ml/100 g; storage at 150 C is recommended (Ref. 5). The development by Chew (Ref. 5a, b) of finite element calculation techniques for the diffusion of hydrogen from both butt and fillet weld joints has provided a sounder basis for the specification of postweld heat treatments to reduce the hydrogen to acceptable levels (Fig. 8).

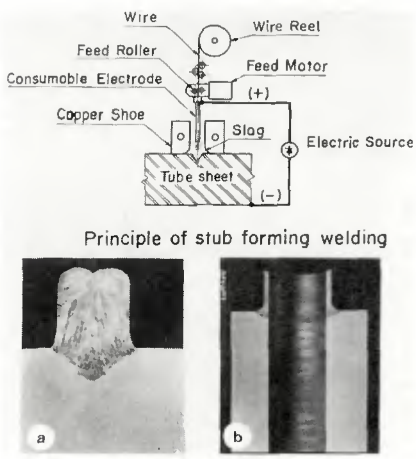

Fig. 6 — Tube to tubesheet welding of FBR using weld forming (Ref. 3): (a) as welded; (b) after finishing

The assessment of cold cracking susceptibility has been the subject of considerable work of Commission IX of the International Institute of Welding which has added greatly to our understanding. Granjon at the Paris Institut de Soudure (Ref. 6) has pioneered the use of implant tests to assess the susceptibility of materials; this work has shown clearly the higher susceptibility of the steel when welded with rutile, rather than basic, electrodes and has indicated that maximum hardness alone does not provide a good guide to cracking susceptibility. It is now, with consideration of the results of other tests (such as the Controlled Thermal Severity Test, much used in the UK), providing a rational basis for specification.

A form of defect that has frequently been found in recent years is that of lamellar tearing. Cooperative work centred at the UK Welding Institute (Ref. 13) has drawn attention to the role that hydrogen can play in assisting the formation of lamellar tears, so that many of the measures that will reduce the risk of hydrogen cracking will also reduce the incidence of lamellar tears. Changes of design have been proposed to reduce or spread out the value of transfer of through-thickness stresses; in other cases the use of special weld joint design involving buttering preparations have been effective.

However, the most effective measure appears to be control of the base metal to avoid selection of plate materials which are weak or of poor ductility in the through-thickness direction. This has been done by applying destructive tests on samples, typically by measuring the reduction of area on through-thickness tensile samples.

More recently a non-destructive test method (Ref. 14) has shown considerable promise; the aligned inclusions which lead to the poor through-thickness ductility also reflect and disperse ultrasonic beams. The effect on the ultrasonic waves appears to depend on the nature of the inclusions, but often the predominant type of inclusion can be inferred for a particular series of plates from experience of the steelmaking process. Calibration curves between ultra-

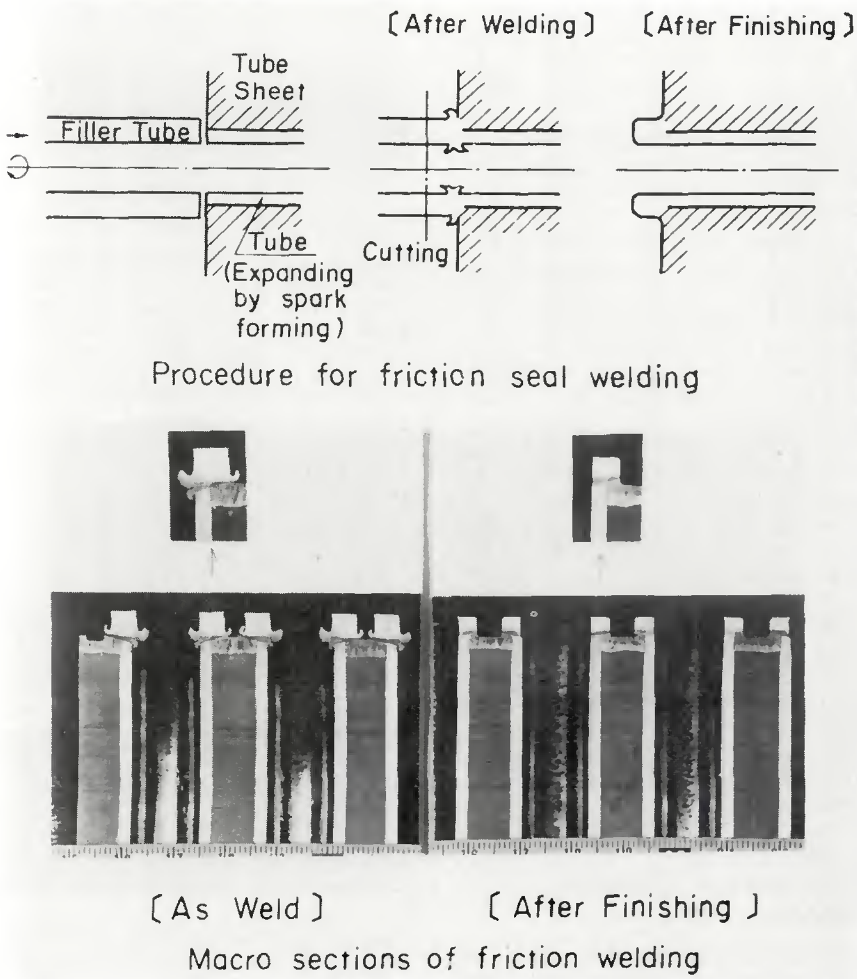

Fig. 7 — Tube to tubesheet joining using spark forming and friction welding (Ref. 3)

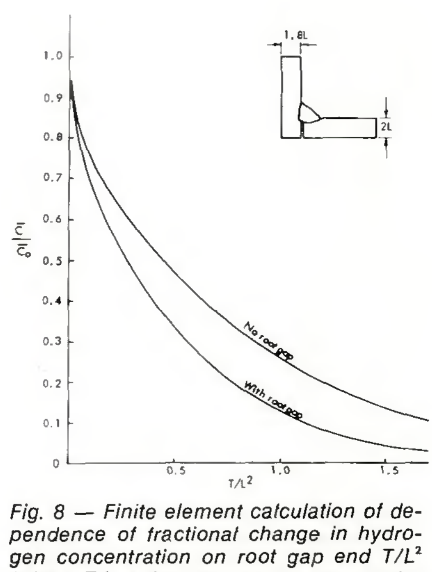

Fig. 8 — Finite element calculation of dependence of fractional change in hydrogen concentration on root gap end T/L^2 (where T is a time temperature parameter ($T = \int_0^t D\,dt$), D is diffusive coefficient, t is time, L is length

sonic response and average through-section ductility (Fig. 9) have been derived for steels containing silicate inclusions and for those with manganese sulphide inclusions and whilst continued work is needed to refine our understanding of this relationship, the method is beginning to be applied.

Turning to reheat cracking, recent work has led to considerably increased understanding of the factors involved in the assessment of the susceptibility of materials to the form of reheat cracking which occurs at higher temperatures. Vinckier (Ref. 8), who is chairman of an energetic working group on this topic for IIW Commission X, has reviewed the various tests, dividing them into assessment tests based on stress relief of formalised welded assemblies, tensile tests on weld simulated specimens and simulation tests of the stress relief cycle on weld simulated specimens.

Table I is reproduced from Vinckier's paper, in which he compared and discussed the tests and presented results on 45 steels using a high temperature tensile test and stress relief simulation tests, both using simulated weld specimens. These tests demonstrated that the fractures were all intergranular and followed the prior austenitic grain boundaries, cracks starting by initiation at microvoids in the boundaries (Fig. 10). The results showed only general similarity in their dependence on steel composition to the proposals of Nakamura and of Ito-Nakanishi (Fig. 11a, b). Vinckier concluded that where possible susceptible steels should be avoided if they were subjected to reheating in welding, in heat treatment after welding or in subsequent service. If this is not practical, then he suggests that:

1. Tensile tests should be carried out at stress relief temperatures on weld simulation specimens heated to 1350 C. A minimum ductility of 20% reduction in area should be required.
2. The design should be checked to avoid as much as possible built in stress raisers and to allow adequate NDT inspection of all joints.
3. By modifying the welding procedure (weld dressing, temper beads, raising preheat temperature, etc.) cracking in susceptible microstructures can sometimes be avoided.
4. Careful NDT inspection should take place after stress relieving the structure and again after final pressure testing.

A somewhat similar study of post-weld heat treatment cracking in high nickel alloy weldments was conducted by McKeown and Scott of the Welding Institute (Ref. 11). Since PWHT cracking is often associated with defects, these authors made use of a fracture mechanics approach to give defect tolerance data from constant load rupture tests on pre-cracked simulated HAZ specimens. Figure 12 shows the results obtained, which rate the alloys in the order of decreasing crack susceptibility generally accepted from practical experience (namely PK 33, 80A, C263 and 75). Again the mechanism of cracking was clearly intercrystalline (Fig. 13) as a result of triple-point wedge crack formation on grain boundary sliding. The tendency to grain boundary sliding depends on the relationship between grain boundary strength and grain interior

Table 1 — Tests to Determine the Susceptibility to Reheat Cracking (Refs. 8, 12)

Stress relief of welded specimens	Tensile tests at high temperature	Stress relief Simulation Tests
BWRA ring (a)	Stress relaxation (g)	Slit tube (l)
Restrained butt weld (b)	Gleeble specimen (f)	Fracture mechanics (m)
Restraining jig (c)	Dead loss stress rupture (j)	Bend specimen (n)
H-type restraint (d)	Implant specimen (k)	Elastic strain (o)
Strained root bead (e)		Plastic strain (p)
Lehigh restraint (f)		
CTS specimen (g)		
Notched U-bend (h)		

(a) Glossop, B. A., Eaton, N. F., Boniszewski, T., Met. Constr., vol 1, Feb. 1969.
(b) Cadman, R. Discussion on Heat Treatment Cracking, Met. Constr., vol. 1, Feb. 1969
(c) Tanaka, Jr. IIW Doc. X-568-70.
(d) Nakamura, H., Naiki, T., Okabayashi, H. IIW Doc. IX-648-69 and X-531-69.
(e) Nose, J., Katsube, C. IIW Doc. X-617-71.
(f) Pense, A. W., Meitzner, C. F., Weld. Journ. vol 48, Oct. 1969, pp 431s-440s.
(g) Murray, J. D., Brit. Weld. Journ., vol. 14, 1967, pp 447-456.
(h) Ito, Y., Nakanishi, M., IIW Doc. X-668-72.
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(k) Granjon, H. Debiez S., Soud. Techn. Conn. vol 25, May-June 1971, pp 216-217.
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(m) Baker, R. G., Dolby, R. E., Watkinson, P., Conf. in Weldability of Structural and Pressure Vessel Steels, The Welding Institute, London, Nov. 1970.
(n) Doty, W. D. Private Communication.
(o) Faber, G., Maggi, C. M. Arch für Eisenhüttenw., vol 36, 1965. pp 497-500.
(p) Vinckier, A. G., CEGB Conf. Paper 16, Sept. 1972, Southampton.

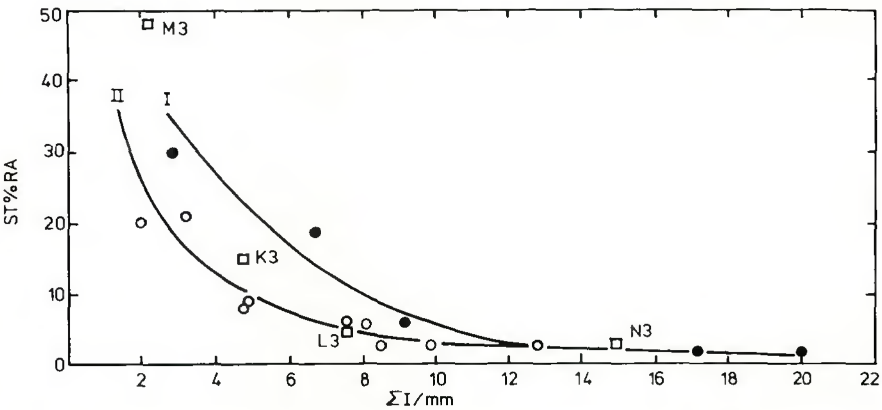


Fig. 9 — Use of ultrasonics to assess steel for susceptibility to lamellar tearing; final correlation between ultrasonic signal Σ 1/mm and ST%RA including results from unknown plates. O—Al treated steels; •—non-Al treated steels; □—Al treated 'unknown' steels

Fig. 10 — Scanning electron micrograph of etched metallographic cross section showing rows of voids on the prior austenitic grain boundaries (Ref. 8). X 6000, reduced 60%

strength, this depending in turn on segregation and precipitation, as can be seen from the effect of aging on susceptibility. Heat treatment of alloy PK33 at 1000 C to remove carbon and chromium from solid solution made that alloy much less susceptible to cracking.

The occurrence of underclad cracking in pressure vessel components has led to a worldwide study which has recently been reviewed for a U.S. PVRC Task Group by Vinckier and Pense (Ref. 12). These cracks occurred only in the coarse grained zone, typically about 3 mm deep and 10 mm wide below the overlapping bead position of high input cladding on certain pressure vessel steels.

In the main, such cracks were shown to be reheat cracks occurring in a relatively narrow region as a result of the localisation of residual stress and of temperatures and thermal strain cycles. A cooperative survey involving questionnaires on materials manufactured by 5 European, 5 U.S. and 1 Japanese firm showed that the problem almost exclusively occurred with the SA 508 Class 2 steel and it was found that of the 34 high input welded cases using this steel, 24 showed cracking sensitivity whilst 10 did not (Table 2). Statistical analysis showed that the nonsusceptible heats were lower in carbon, chromium and phosphorous but higher in silicon and manganese. The survey gave support to the effectiveness of the Ito and Nakamura formulae for assessing susceptibility from composition mentioned earlier in this paper.

The occurrence of postweld heat treatment cracking has led some welding engineers to suggest that stress relief heat treatments should be omitted. Such a move is undesirable not only from the point of increasing brittle fracture risk but also by increasing the possibility of high temperature cracking in service or of other types of cracking. For example CEGB have found that in 2% Cr-Mo steels transverse weld cracking can be associated with the low ductility (~½%) of the weld metal if it is not tempered for more than 3 h at least at 700 C. Weld metal transverse cracking depends also on the extent of columnar grains, and like several other forms of cracking may occur more frequently with high input processes or large size electrodes leading to large bead sizes and coarse microstructures. Price (Ref. 17), following a major CEGB study has concluded that satisfactory reliability from such cracking can be achieved by using small grain electrodes, wide angle preparations (15-20 deg preparation angle), good overlap to refine microstructure so that grain size is 30 microns or finer, and finally postweld heat treatment to reduce residual stresses.

Assessment of Properties of Weldments

Improved knowledge of the properties of weldments, and how these depend on the welding processes, materials, welding conditions and postweld heat treatment has an obvious relationship to improved reliability. This does not only apply to mechanical properties; because the chemical composition or metallurgical structure of the weld differs from that of the base metal, corrosion or stress corrosion effects have sometimes been found to occur locally to a weld. This may only occur under very specific environmental conditions.

For example, laboratory tests (Ref. 15) on alloy 800 tubes welded with Inconel 82 filler in a range of conditions intended to simulate those which may arise in high performance boilers showed that in most cases in spite of considerable differences in local metallurgical structure, all the various conditions showed similar corrosion behaviour. An exception was in 350 C tests in oxygenated saline solutions containing considerable caustic (0.6%

Table 2 — Comparison of Chemical Compositions of Susceptible and Nonsusceptible Groups of SA 508 Class 2 Steel (Ref. 12)

Element	Mean wt% susceptible group	Mean wt% non-susceptible group	Statistical confidence level, %
C	0.210	0.205	99
Cr	0.380	0.365	95
P	0.0091	0.0082	85
Si	0.258	0.278	90
Mn	0.679	0.700	90
Parameter: P_{SR}(a)	−0.221	−0.286	85
Parameter: ΔG(a)	0.548	0.468	95

(a) See Fig. 11 (a) and (b)

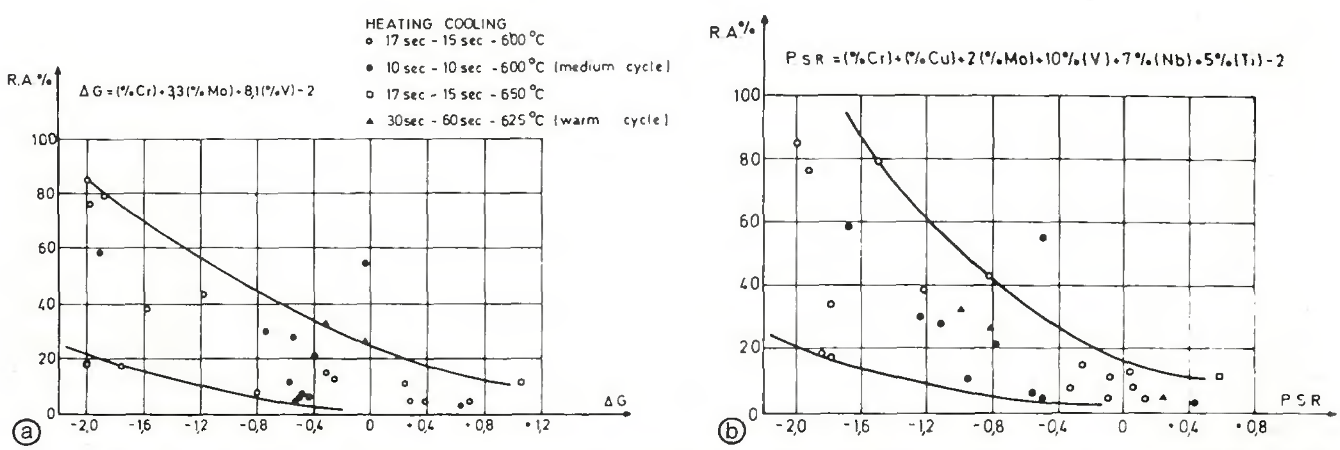


Fig. 11 — (a) Reduction of area in unnotched tensile tests at stress relief temperature on weld-simulated samples (T_{max} = 1350 C) compared with Nakamura ΔG values (Refs. 8, 9). (b) Comparison of RA% in unnotched tensile tests at stress relief temperature on weld-simulated samples (T_{max} = 1350 C) compared with Ito-Nakanishi parameter P_{SR} (Refs. 8, 10)

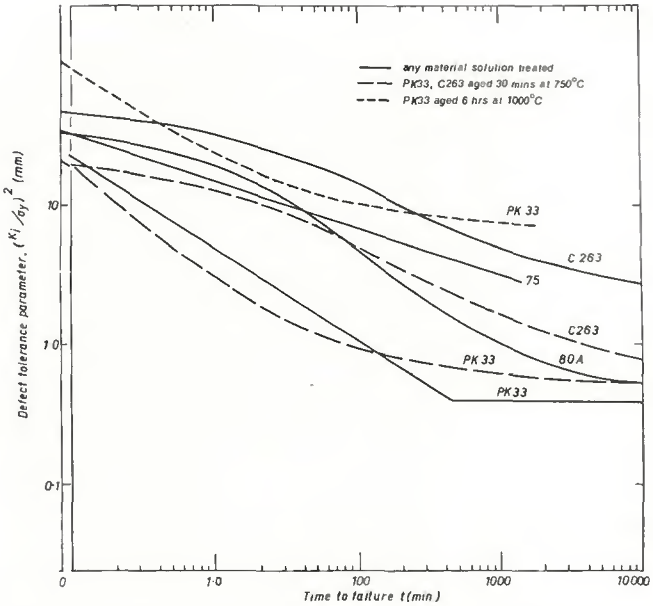


Fig. 12 — Comparison of reheat susceptibility of different Ni base alloys by defect tolerance parameter calculated from constant load notched rupture tests (Ref. 11)

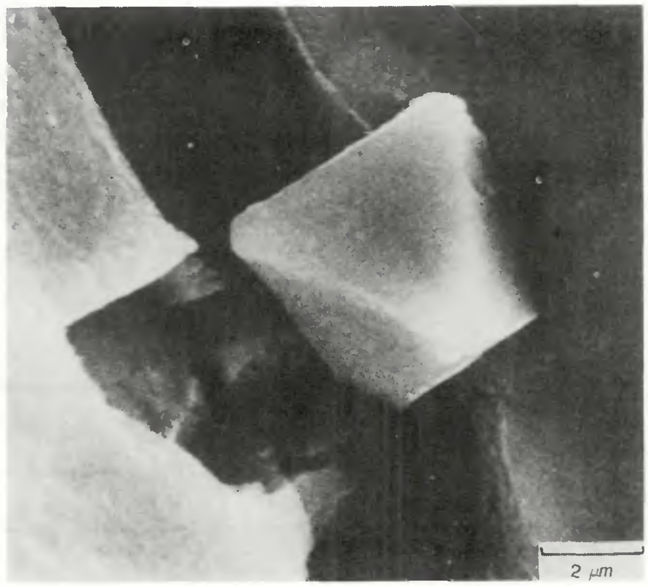


Fig. 13 — Scanning electron micrograph showing grain boundary particle pulled cleanly from one grain during cracking (Ref. 11)

NaCl with 2.5 $MNm^{-2}O_2$ and 4% or more NaOh). Branched intergranular cracking was observed with severest attack in regions of grain growth near welds (Fig. 14). Whilst tests in pure superheated steam at 500-600 C showed little corrosion, some oxidation including internal oxidation was found in the weld metal. Results of this type stress the need for detailed corrosion tests in some design applications, and the recognition that weld chemistry and weld process control may be essential to get the required assurance on corrosion and corrosion fatigue behaviour.

Another field of weldment behaviour in which there has been only limited work has been that of creep behaviour. The work on reheat cracking referred to earlier in this paper has shown that welding can lead to local impairment of high temperature ductility and indeed failures in power plant service have occurred because of this. The problem is complex because the creep strength properties are also varied, so that the distribution of the local strains depends on the actual component and weld geometry. Increased understanding is sought on how best to predict the behaviour of a welded component from uniaxial tests on composite or weld simulated materials.

The UK Central Electricity Generating Board (Ref. 16) has recently taken the lead on an important programme to this end in which welded vessels, designed so that they provide checks on proposed creep strain analysis methods will be tested by internal pressure loading and the results compared with those from welded tube and uniaxial creep and creep rupture tests, of up to 20,000 h duration. Figure 15 shows the type of vessel under test, and tabulates the programme, which will be supported by the tube testing programme shown in Table 3a and the uniaxial tests of Table 3b.

The use of large scale welded samples to assess the mechanical properties of weldments has of course been applied previously, particularly with respect to brittle fracture and fatigue behaviour. Tests using notched and welded wide plates have recently been applied on a sufficient scale to provide the basis for a British Standard (BS 1515 Appendix C and the more recent draft BS Master PV Code) which details the minimum temperatures for use of particular welded steels in pressure vessels. The effect of postweld heat treatment in lowering this temperature is shown clearly by the test results shown in Fig. 16. The results of the fatigue tests have mainly been of use in establishing the significance of defects. It is worth stressing however the very large effect that flaws such as toe cracks or undercut at the toe of a fillet weld joint can have on its fatigue life, a major factor in the improvement in fatigue properties that can result from grinding the fillet before service (Fig. 17).

Perhaps the most important reliability aspect of the assessment of weldments in recent years has been the interpretation of large scale test results to provide a better understanding of the engineering significance of flaws and defects so that inspection acceptance levels can be

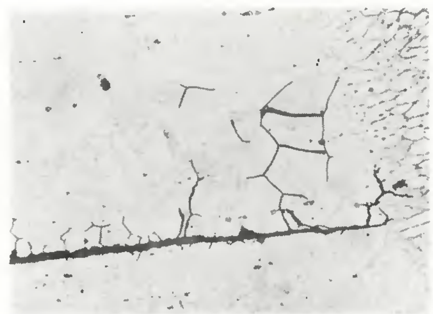


Fig. 14 — Micrograph showing severest attack near grain growth region near alloy 800 welds after tests at 350 C in 0.6% NaCl, 3% MnO_2, 4% NaOH solution

based on experimental data rather than on subjective experience. Such an approach can be justified on reliability grounds since weld repairs are often themselves the source of further defects or changes in mechanical properties particularly if they occur in materials that show progressive grain growth on each welding cycle, or in circumstances where postweld heat treatment is not possible. From the fabricator's viewpoint, a rational basis for acceptance standards makes sound economic sense.

Data collected by Salter and Gethin (Ref. 18) from 599 pressure main seams totalling 2336 m in length showed that these contained 806 defects which had to be repaired on present rules. However examination of these defects (Table 4) showed that only 19% were planar defects (cracks or lack of fusion), so that use of a "fitness for purpose" acceptance standard would have reduced the num-

Table 3a — CEGB Tube Bursting Programme (Ref. 16)

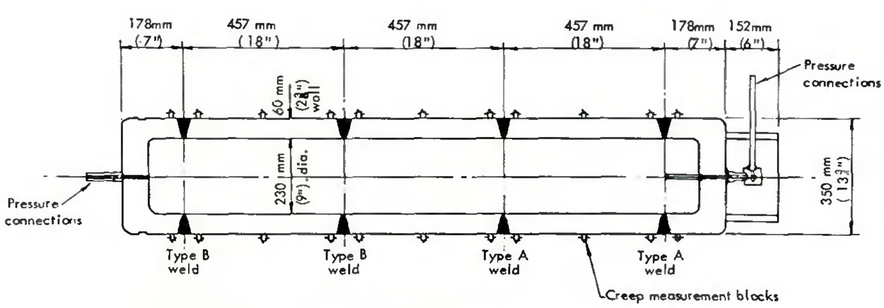
Hoop stress	Hoop:axial stress ratio	Weld metal heat treatment (a): Mild steel SR	Mild steel N/T	1CrMO SR	1CrMO N/T	2CrMO SR	2CrMO N/T	½Cr½Mo¼V SR	½Cr½Mo¼V N/T
For	1 : 0.5	*	*	*	*	*	*	*	*
10,000	1 : 0.75					*			
hour	1 : 1	*	*	*	*	*	*	*	*
life	1 : 1.5								
For	1 : 0.5	*		*		*	*	*	
20,000	1 : 0.75					*			
hour	1 : 1	*		*		*	*	*	
life	1 : 1.5					*			

(a) SR — stress relieved; N/T — renormalised and tempered

Table 3b — Uniaxial Tests in CEGB High Temperature Weldment Programme (Ref. 16)

Material	Variant	Condition[a]	No. ot creep tests	No. of rupture tests (crossweld)
Mild Steel	Vessel ½ plate	SR	6	4
1CrMo	Vessel ½ weld metal	SR	6	16
2CrMo	Vessel ½ plate	SR	10	12
	Vessel ¾	As-welded	3	4
	Weld metal	Extended SR	3	4
		N/T	3	4
		Low Temp SR	3	4
½Cr½% ¼V	Parent 1 & 2	SR	6	4
	Parent 3 & 4	As welded	3	—
		Extended SR	3	—
		N/T	3	—
		Low Temp SR	6	—
	HAZ 1300 C	SR	6	—
	Vessel ½			
	HAZ 950/1000 C	SR	6	—
	HAZ 750/800 C	SR	6	—
	Weld metal	SR	6	—
	1300 HAZ	As-welded	3	—
		Extended SR	3	—
		N/T	6	—
		Low Temp SR	3	—
Total			100	52

(a) SR — stress relieved; N/T — renomalised and tempered



Vessel	Weld A	Weld B
1	Mild steel	½Cr½Mo¼V
2	1CrMo	2CrMo
3	2CrMo Renormalised and tempered	2CrMo As welded
4	2CrMo Low temp. stress relief	2CrMo Extended stress relief

Fig. 15 — Design of welded vessel for CEGB high temperature comparative tests (Ref. 16)

ber of repairs required from 806 to 153, and reduced the number of seams repaired from 258 to 70. In the interests of both economy and reliability it is very desirable that further such surveys are made, preferably on an international basis, and preferably in sufficient detail to allow a comparison of the reliability of different welding processes.

In the Welding Institute survey (Ref. 18) it was noted that each firm had its own characteristic pattern of defect occurrence which could be correlated with the welding processes used and the materials being welded. In particular longitudinal electroslag showed a low incidence of defects (defect length/seam length total 0.36%; planar defects 0.25%) compared with submerged arc (total 1.6% longitudinal, 2.36% circumferential; planar defects 0.9% longitudinal, 0.36% circumferential). Extension of this type of analysis would provide the evidence on average rate of production of flaws of particular types in particular size ranges, evidence much needed for probability assessments of reliability.

"Fitness for purpose" acceptance standards have been put forward in several parts of the world, following the 1972 International Institute of Welding public discussion in Toronto and continued efforts of a Working Group of IIW Commission X. In the United States, ASME XI 1974 edition* describes methods based upon linear

*1974 ASME Boiler and Pressure Vessel Code, Section XI — Rules for Inservice Inspection of Nuclear Reactor Coolant Systems.

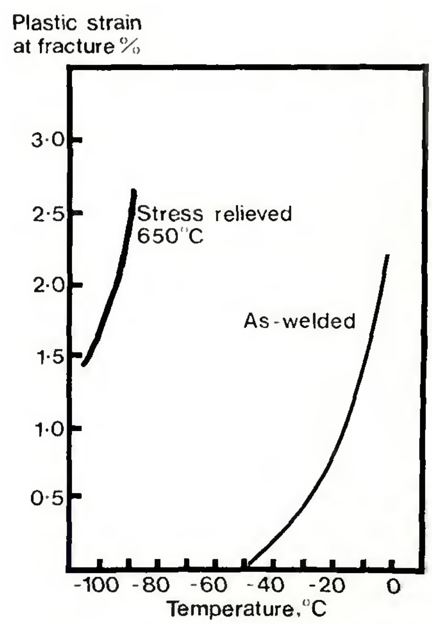


Fig. 16 — Effect of thermal stress relief on wide plate test results for carbon-manganese steel (Courtesy of the Welding Institute)

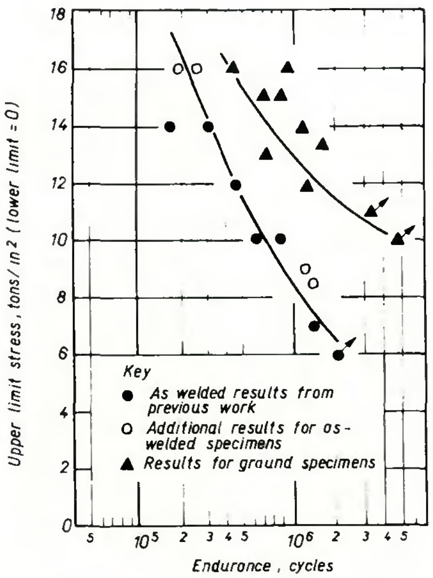


Fig. 17 — Effect of grinding of fillet on fatigue endurance of welded samples (Courtesy of the Welding Institute)

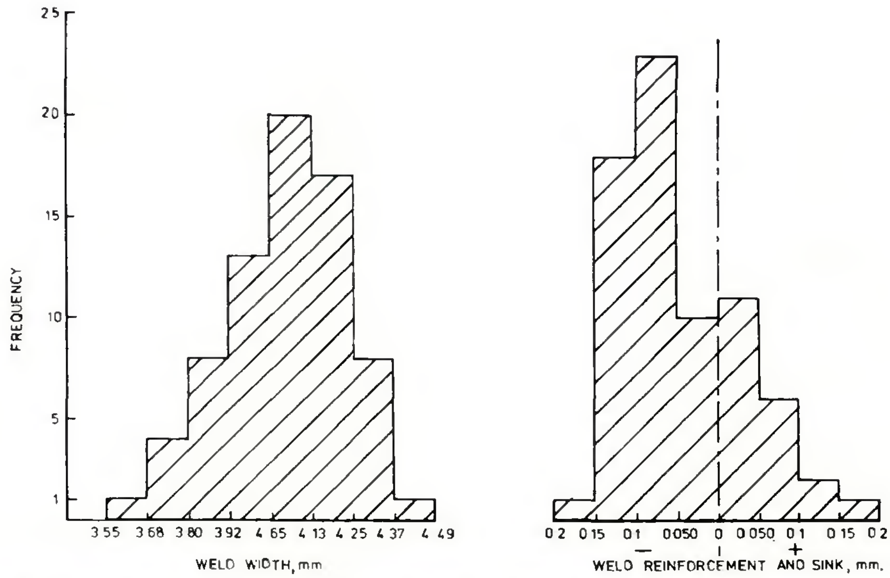
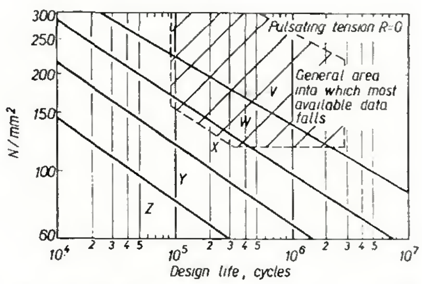


Fig. 19 — Histograms of weld dimensions in process-controlled control-rod closure weld (Ref. 22)



Key: Defect length	Porosity %
W 15-5 mm AW, 5 mm SR	0
X 10-25 mm AW, No max SR	8
Y No max	20
Z No max	20

Fig. 18 — Fatigue diagram showing design quality levels. AW = as welded, SR = stress relieved

Table 4 — Summary of Pressure Vessel Main Seam Defect Data Expressed as Percentages (Ref. 18)

Percentage analysis	Cracks	Lack of fusion	Porosity	Inclusions	Total critical defects	Total non-critical defects
Number of defects	14	5	14	67	19	81
Length of defects	14	8	7	71	22	78
Volume metal removed	8	5	3	84	13	87
Seams with defect / Total no. def. seams	27	8	27	71	27	73
Total defect length / Total seam length	0.27	0.16	0.14	1.27	0.43	1.41

elastic fracture mechanics and on data obtained from the Heavy Section Steel Technology programme of large scale fracture toughness, fatigue and pressure vessel tests. In Norway, Det Norske Veritas (Ref. 19) have described acceptance criteria for welds in LNG tanks in ships. In the UK, a British Standard is being drafted by Committee WEE37, partly based on cooperatively sponsored work using fatigue and brittle fracture tests on sizeable specimens and on welded pressure vessels (Ref. 20) containing weld seams of controlled porosity.

For example one vessel showing continuous slag defect in the weld withstood 1½ million cycles with a membrane stress of 23,600 psi without leaking. This gave support to the values achieved in small specimen tests, on which Fig. 18 was based. This figure indicates the stress limits for 5 quality levels, V being the highest quality with very limited slag inclusions and porosity, whilst quality Z has no limit on individual slag inclusions, allows 20% porosity and increased tolerance for planar flaws. Present ISO/TC11 acceptance standards correspond approximately with the most severe of those for quality, indicating that the present standards are conservative for all structures where the fatigue usage falls on the lower stress/cycle side of the line dividing class W from class X in Fig. 18.

The draft shortly to be proposed by WEE37 is intended to give guidance to the welding industry (Ref. 21) and will provide general rules by which standards for particular products should be derived. The flaws are categorised as planar defects (cracks, lack of penetration (fusion), nonplanar defects (solid inclusions, gas pores, shape imperfections including undercut), the acceptance limit being derived from laboratory testing and experience for the nonplanar flaws, and from fracture mechanics principles (supported by laboratory tests) for the planar flaws. For brittle failure, the limits on non-planar flaws are defined by their height normal to the maximum stress, and by the need to avoid their masking other defects (Table 5). For planar defects the acceptable size, and the detailed method, depends on the total stress in the region of the flaw. Primary, thermal, residual and peak stresses must be added together and if the sum is less than yield then the stress intensity approach (K) of linear elastic fracture mechanics (LEFM) is used. Calibration curves for partial thickness defects, for direct and bending stresses are given in the standard, the total K value for post-through flaws being:

Table 5 — Provisional Limits[a] for Nonplanar Defects — Brittle Fracture (Ref. 21)

Inclusions	Porosity	Individual pores	Undercut
Max. height or width 3 mm, no max. length	Max. % projected area on radiograph 5%	Max. diam, the lesser of e/4 or 6 mm; e = thickness	Maximum depth 1 mm provided no interference with NDT

(a) The above limits apply to steels with yield strength up to 480 N/mm^2 and Charpy V-notch energy of 40 J at minimum service temperature. For other materials minimum toughness 1300 $N/mm^{-3/2}$

$$K = (a/Q_0)\,(\sigma_m\, M + \sigma_b\, M_b)$$

a = defect ht (surface flaws) or ½ defect height (embedded flaws)
σ_m = direct stress component normal to flaw
σ_b = bending stress component normal to flaw
M_m, M_b = factors from calibration curves for given defect/thickness
Q = defect shape factor

A flaw is acceptable only if its estimated size (allowing a large factor for uncertainty in ultrasonic derivation of size) is such that the resulting total K value is less than 0.7 of the K_{Ic} for the correct material, rate and temperature conditions.

For as-welded structures it must be assumed that there are residual stresses of yield point level. In such cases, and in others where total stresses exceed the yield stress, the British Standard does not use LEFM (or its extensions by J or Equivalent Energy methods) but on the Crack Opening Displacement (COD) concept. A flaw is regarded as acceptable if its equivalent defect size parameter $\bar{a}$ is less than a tolerable flaw size parameter $\bar{a}_m$ where:

$\bar{a}_m = C\,(\delta/e_y)$ which where appropriate is equivalent to:
$\bar{a}_m = C\,(K_{Ic}/\sigma_y)^2$

δ_c = critical COD for material
K_{Ic} = critical stress intensity factor for material
σ_y = yield strength of material
e_y = yield strain of material

The value of the constant C is obtained from a curve in the draft standard in which C is plotted against the ratio of total (applied) stress to yield stress, this being extended above unity by strain concepts based on experimental results of wide plate and COD tests, the design curve being so drawn as to give a factor of safety of 2 for fracture assessment alone (i.e., with additional safety factors for uncertainties in material properties and in NDT estimation). The COD analysis has recently been extended to deal with part-thickness flaws, and in both cases rules for multiple planar flaws are defined.

Another problem is the fracture criterion to adopt for materials which show a stable crack growth together with a flat deflection/local curve near maximum load; one contribution to WEE37 has suggested that in these cases the critical value should be the COD corresponding to 95% of maximum load.

Critics of the "fitness for purpose" approach have objected to it for potentially lowering quality standards. This is unjustified since such an approach directs attention to getting reliability through emphasis on the important aspects of quality (e.g., freedom from cracks and lack of fusion). Moreover it would be necessary to take action to review welding procedure if flaws were frequent, even if they were individually of an acceptable size, since in such cases there would be doubt on the validity of the analysis, as the material properties may (with the quality) be differing from that derived in the procedure or type tests.

Process Control for Reliable Quality

An important avenue of development of welding processes is to provide consistency in product and freedom from defects by closer control during welding of the welding conditions, the so-called "real-time control." Most of the approaches have been based on controlling the conventional welding parameters against time, namely welding current, welding speed, joint gap, arc gap, electrode angle, electrode feed, inert gas supply, starting and tail-off conditions. In the UKAEA Mark IIIA weld controller, a small digital computer specifies the welding programme (i.e. current variation and speed of movement) for each of up to 30 time "blocks" to a dc power source and to digitally controlled dc servo motors for programme speeds and to provide changeover matrices. The 9 digit solid state switched power source is under direct digital command of the computer, each of 8 current levels (0.5, 1, 2, 4, 8, 16, 32 and 64 A) having one ON and one OFF thyristor, the 128 A level having 2 ON and 2 OFF thyristors.

Inductor/resistor circuits on the six lowest current circuits limit the voltage recovery rate at the thyristor cathodes to block off the current at the ON thyristor according to programme. Elevated voltage and ionisation units are provided to aid spark starting. The dc servo motors are controlled in speed by differential variation in field current supplied by a servo amplifier against a reference signal obtained from the controlling computer via a digital/analogue converter. Motor reversal can be achieved by using relays to transpose polarity. A simple controller of this type can be used to operate several stations on many different welding programmes, and can be of value both in production and in development.

In development work, considerable economies can result from the ability to programme systematic variations in the weld parameters. Once the optimum conditions have been so established they can be programmed into any similar system for production.

A typical example (Ref. 22) is to make the welds which seal the ends of nuclear reactor control rod tubes in AISI 316 steel, 21.6 mm OD, 1.2 mm wall thickness. A plain butt weld is used with the end cap appropriately machined to provide a small amount of integral filler. A full penetration, leak tight joint free from major defects is required and the weld bead surfaces must also be kept within close dimensional tolerances. In the developed process, the weld is made at 50 A reducing 10 A before final arc extinction in a total weld time of 40 s. Figure 19 shows that for a mean weld width of 4.1 mm and a weld surface that shows on average a very slight sink, 95% of the welds will lie within ±0.35 mm width and ±0.15 mm surface level.

The requirement for high reliability for the tube/tubesheet welds in the fast reactor, which separate liquid sodium from steam/water, has also been tackled by process control. The favoured weld joint configuration, which avoids design crevices and reduces risks of defect due to tubesheet lamellar weaknesses is shown in Fig. 20. The major requirement is to a satisfactory profile and uniformity of weld thickness, with a smooth reinforcement, and transition and freedom from cracks.

Using the process controller as a development tool (Ref. 22) and mechanised GTA welding from the bore, some 500 welds investigated 14 process variables. The fit of the tube was found to be important, and in later work this was obtained (Ref. 23) by providing a short spigot on the end of the tube, selecting the tubesheet bore size so that the spigot was a clearance fit in the bore, whilst the outer part of the tube butted on to the top surface of the tube sheet. For the austenitic tube/tubesheets assemblies in the higher temperature heat exchangers, cracking due to grain boundary films of iron-niobium eutectic in the weld-end region was avoided by control of the tail-off sequence to control the cooling rate and hence the thermal stress (Fig. 21).

Requirements to extend the application to AISI Type 316 tubes greater than 2.3 mm thick, and for different tube diameter/wall thickness ratios led to further problems. With some geometries it was necessary to incorporate a short length of 17% Cr material at the end of tube which was fused in with some of the normal tube material and some of the tubesheet material to give sufficient delta ferrite to avoid microfissuring. Modification of the tube material composition specification replaced this approach as a long term solution.

Other problems with thicker tubes was tube movement and joint variation during welding together with erratic advance of the weldpool penetration front. These aspects led to the use of a series of overlapping restarted welds, each start taking place with the same boundary conditions achieved by a current-pulse programme. An important aspect is the centralising of the tungsten torch by an expanding collet in the borehole and precise longitudinal adjustment with the aid of an audible touch-down circuit. The programme will shut down if excessive arc gap, poor electrical contact, insufficient gas shielding, low flow or pressure in the water and gas supplies or if strong arcing occurs. During welding it was found that the constant power mode gave the best control on external fillet size and this was achieved by using a Hall effect multiplier to allow the arc voltage to exert a control of the current. The production controller also provided for change over from argon to argon-helium shielding after arc initiation and for feed-back monitoring on all the important weld parameters. The technique was proved by thorough inspection using techniques developed by the UKAEA Risley Engineering & Material Laboratories including TV magnifying intrascopes, ferrite/selastometer plugs for recording magnetic inspection in the ferritic steels, electrical weld thickness gauges, rod-anode x-ray and thulium source gamma ray with flexible cassettes, and ultrasonics from a water irrigated, twin crystal probe (Ref. 24).

A somewhat different approach to weld process control has been developed by Smith (Ref. 25) and Boughton of CEGB Marchwood Laboratories. This method is based on the direct observation of an important requirement of the weldment (in this case, penetration) and using this to provide a self-adapting control. The procedure is to measure the temperature distribution on the back face of the weld using a silicon photodiode sensitive to the incident radiation. It is found that this must be restricted to radiation in the 0.45 to 0.55 micron wave bands (blue green to yellow green) in order that all metal temperatures below about 1300 C be rejected and only the radiation from molten or near molten metal received; this was achieved by the use of filters.

The amount of energy thus detected depends on the penetrated area; if the penetration increases the pool width by a factor k, the observed energy will be increased by a factor of k^2, making the system very sensitive to changes in the critical parameter, width of penetration. The diode, typically 2.8 mm diam of the BPY68 type, has to be positioned to optimise the energy response, seeing as large an area of the back face of the weld as possible and taking account of the inverse square law effect on distance.

Figure 22 shows an arrangement used on a tube/tubesheet weld. In this process the welding current is held constant throughout weld pool growth with the electrode stationary, incremental movement occurring only between welding pulses. The heat input, and thus the dimension of the weld pool, then depends on the duration of the pulse alone. Control in this case is easy; when the voltage analogue of the weld pool area determined from the silicon diode circuit reaches a preset level, the welding current is terminated. After this, a one second cooling period and a two second traversing period occur before the pulse current is reinstated and the weld completed in a series of overlapping spots. The device has also been applied to pulsed GTA orbital tube/tube butt welds on 40 mm diam 1Cr-½Mo boiler tube. Problems to be overcome were the removal of the diode after welding, the heating of the diode in the confined space, smoke generation within the tube and the low angle of view of the weld pool.

The principles involved in self-adaptive control by penetration measurement have been extended to provide such control where access to the back face is not possible. In such situations, measurement is made of the width of the weld pool on the front face. Boughton (Ref. 26) has shown that the weld pool depth z is related to the weld pool width y and the welding voltage V, current I and speed U by a general relationship of the type:

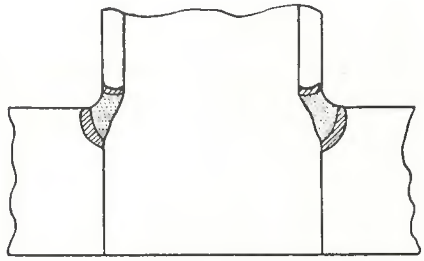


Fig. 20 — Joint configuration of heat exchanger tube/tubesheet weld for a sodium cooled fast reactor (Ref. 23)

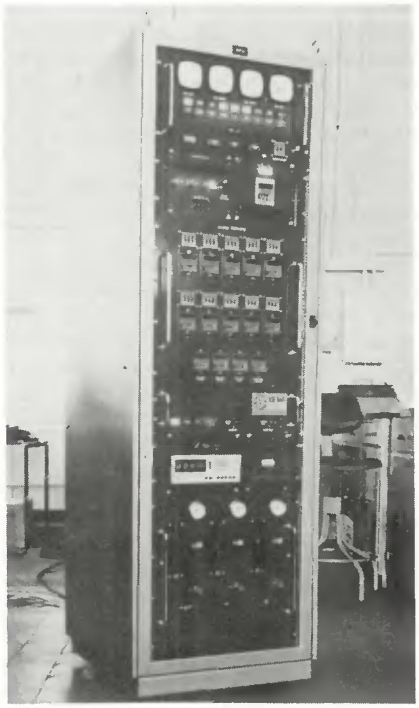


Fig. 21 — Mk 7 tube/tubesheet weld programmer fitted with pulsing, indexing and monitoring modules (courtesy of Babcock & Wilcox Operations, Ltd)

$$Z = \frac{VI}{Ayu + B} - C$$

where A B & C are constants

In GTA welding the arc length, and thus the voltage V, are maintained reasonably constant so that the possible control variables are current I and speed U; either or both of these can be adjusted to provide a required pool depth (penetration) by measurement of the width of the weld pool. Experimental work has shown some promise using a strip of 256 silicon diodes each 0.1 mm wide, total length 25 mm, the width of the weld pool being indicated by the number of these diodes which indicate receipt of radiation from the molten metal.

The principle of control of weld

quality by energy input can be extended to other types of welding. One example is for arc-stud welding, in which an arc (typically about 1000 A) is struck between the end of a stud and the plate to which it is to be welded, and maintained for about ⅓ s after which the stud is plunged into the molten pool to achieve fusion. In some cases it is necessary that such studs be load carrying and thus the joint should have adequate ductility.

Figure 23 shows that welds with low input energy (<9 kj) can fail with zero ductility, this being strongly associated with porosity and lack of fusion. At first, control by indirect measurement of energy by measuring the after weld length was tried on the basis that burn-off length was proportional to weld energy. After-weld length measurements are inaccurate and dependent on preweld length and end contour variations, so that direct measurements of weld energy are preferred (Ref. 27). This was done by measuring the voltage and current, feeding to an energy meter, and tripping the supply at a time when the energy reaches a preset level. At this stage the stud should be plunged into the molten pool, and monitoring of this requires a transducer to check the plunging movement; this will also show a wrong reading if the small aluminium tip on the stud provided for deoxidation was absent, giving a high weld porosity. Thus whilst process control is by energy, quality monitoring requires that both energy and change in length are comparable with preset requirements.

The Role of Inservice Inspection

The traditional role of nondestructive examination has been to add to the other methods of quality assurance and quality control, so that on average the reliability of the product, as affected by the incidence of flaws, is acceptable. On this basis, examination can be done by sampling and the choice of methods not restricted only to those detecting flaws which will effect the service behaviour. The emphasis on fitness for purpose assessment of the significance of flaws, and on the very high assurance of reliability required for such a component as the steel pressure vessel containing a nuclear reactor core has changed the role of nondestructive examination (NDE) to one of attempting to detect all residual flaws which may effect service behaviour. Thus the final reliability of the product (which for a reactor pressure vessel should be better than one failure in 10^7 vessel years) depends on the reliability of the welding process in not producing planar defects over a certain size, the reliability of the NDE process in detecting and leading to repair action on such defects, and the probability of any residual defect of such a size leading to failure.

These arguments lead to the requirement of an NDE system aimed at 100% volumetric examination in the areas where defects may arise, by a method suitable for detecting and sizing any planar defects, and especially suitable for determining the dimension that is normal to the largest applied stress. Further, the risk of the production or extension of flaws in further fabrication, in heat treatment, in transport or assembly has led to the concept of such an overall NDE being made immediately before the start of service life. The prospect of flaw growth by fatigue, creep or corrosion and the effectiveness in conventional plant of operational inspection at detecting incipient failure has provided the argument for extensive inspection of the welds in the primary coolant circuit at intervals throughout their service life. Suitable manipulators have been developed to carry out such examinations remotely on active steel vessels, and there is now considerable experience of their effectiveness.

The requirement for such examinations has its implications on design, fabrication and inspection during fabrication. At present the only method which can achieve the volumetric search and sizing requirements is the meticulous scanning by ultrasonic beams. This emphasis on ultrasonics rather than radiography makes it desirable that inspections throughout fabrication include thorough

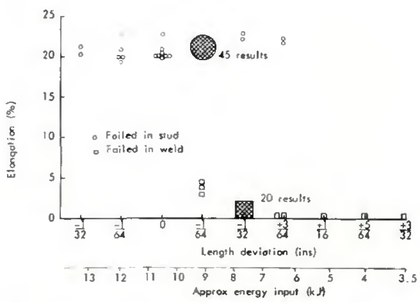


Fig. 23 — Variation of stud weld ductility with length and energy input (Ref. 27)

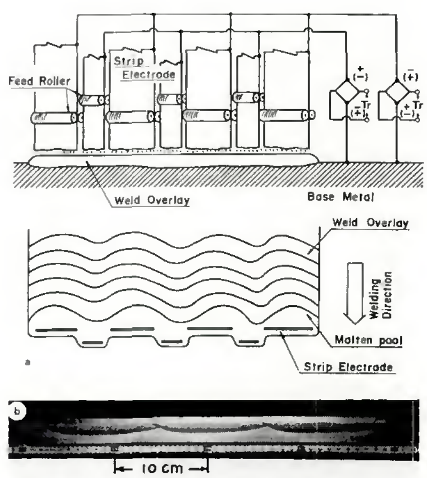


Fig. 24 — (a) Principle of weld surfacing process by multiple strip electrodes; (b) macrostructure of surfacing weld by multiple strip electrodes (Ref. 3)

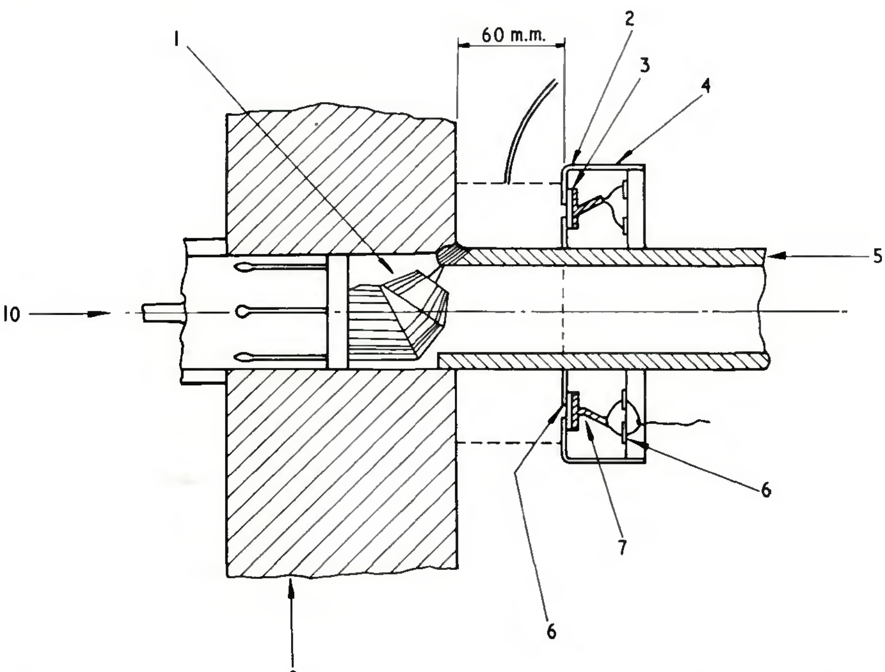


Fig. 22 — Components of the system for welding a tube/tubesheet assembly: 1-Welding head; 2-heat filter; 3-green filter; 4-metal box; 5-tube; 6-PCB connectors; 7-diode; 8-6 mm window; 9-tubesheet; 10-stepping motor drive (Ref. 25)

examination by ultrasonic techniques. It is also necessary that component design permit access of the ultrasonic tools and also that the geometry be completely inspectable from the accessible surface. Prevention of access by local attachments or by local as-fabricated geometry departing from design must be guarded against.

For vessels clad by surfacing, it is important that the clad surface have a suitable finish both with regard to roughness and to local geometry, and in this respect it is of interest that Sato (Ref. 3) has proposed using a multiple strip electrode assembly with each strip of alternate polarity to provide a very level clad surface, Fig. 24 (a) and (b). The selection of materials and fabrication control to provide a metallurgical condition suitable for inspection is also important — nickel alloys can prove very difficult to inspect by ultrasonics, austenitic steels become easier to inspect with control of grain size and of grain orientation, whilst it is desirable to have inspections of all base metals to reject levels of lamellar defects or of inclusion density which can interfere with ultrasonic examination. Thus the implication of requirements for in-service inspection is for continual interaction and consultation between the designers, metallurgists, welding engineer and inspection agencies.

In-Service Repair

A final aspect of continued reliable operation is the ability to repair a flaw before it becomes hazardous. Access limitations, particularly those due to radioactivity in nuclear plant, make it necessary to use remotely controlled equipment in many cases.

One example was the repair to the austenitic steel primary circuit of the experimental fast reactor at Dounreay, Scotland. In May 1967, while the reactor was operating at full power, an alarm indicated that a leak of the highly active primary sodium/potassium coolant into the leak jacket had occurred; the leak stopped when the reactor was shut down. The location of the leak was in itself a major task, and it was five months after shutdown before it was shown that the leak was not in the main vessel, but at a pipe weld about 45 cm from the vessel wall, in the reactor vault where the radiation field ranged from 0.5 r/h to 5 r/h. Two additional entrances into this vault were cut, and a 3 m length of the 100 mm diam primary circuit pipe and its leak jacket was cut out (Fig. 25). The actual crack was then found in a weld near a thermocouple block and a tee bypass connection. Because of a misalignment, the weld ran off the joint line causing inadequate joint penetration.

Evidence of thermal stress suggested that, as well as dealing with the crack, it was also desirable to cut out all of the seven bypass circuits. A remotely operated glass fibre Al_2O_3 cutting wheel driven at 30,000 rpm by an argon turbine was used to cut out the length of primary pipe containing the defect, and to face up the stub end. After cleaning and monitoring for cleanliness by swabbing, a new pipe was welded in using a specially designed orbital welder (Fig. 26) for which procedures had been developed concurrently on laboratory mockups. In all a labour force of 346 men were used in the vault, although access prevented more than two or three men being there at any one time. Normally each man spent only one day working up to his body dosimeter limit of 1 r, some being

Table 6 — Effect of Different Surfsces on Push-out Strength Following Tube Plugging by Friction Welding (Ref. 30)

No.	Plate condition	Strength kilo-newtons
1	Oxide — light blue surface	142
2	Oxide — 0.1 mm approx.	126
3	Oxide — 0.5 mm thick scale	100
4	Water — weld area submerged	122
5	Oil — weld area covered	151
6	Reweld	128
7	Chipped	146
8	Chamfered 2 mm	136
9	Chamfered 3 mm	Stalled
10	Dust	133

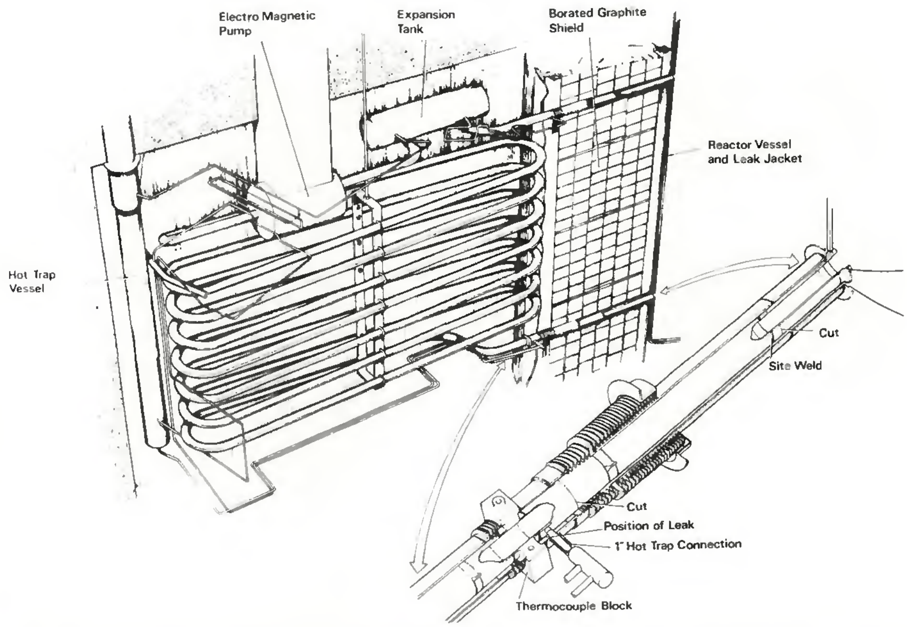


Fig. 25 — General arrangement of heat exchanger and hot trap circuit showing position of leak (Dounreay Fast Reactor, Ref. 28)

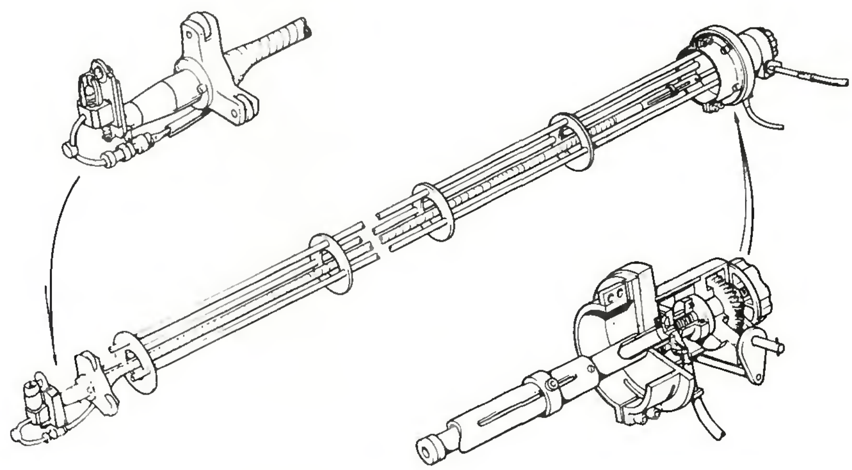


Fig. 26 — Internal welding equipment for DFR primary circuit repair (Ref. 28)

used on about three occasions at intervals. The trouble that this one small weld defect caused emphasises the need for reliability in welding for nuclear power, independent of and additional to the stringent reliability

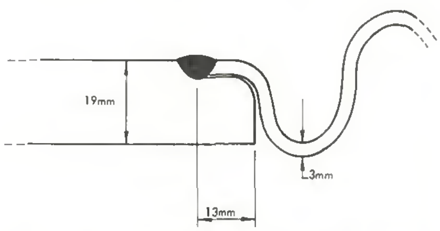


Fig. 27 — Detail of weld in Berkeley bellows joint in which fatigue cracking occurs (Ref. 29)

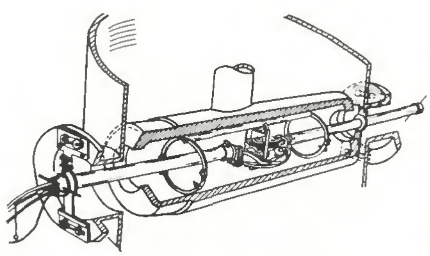


Fig. 28 — Assembly inside header for friction welding of plug (Ref. 30)

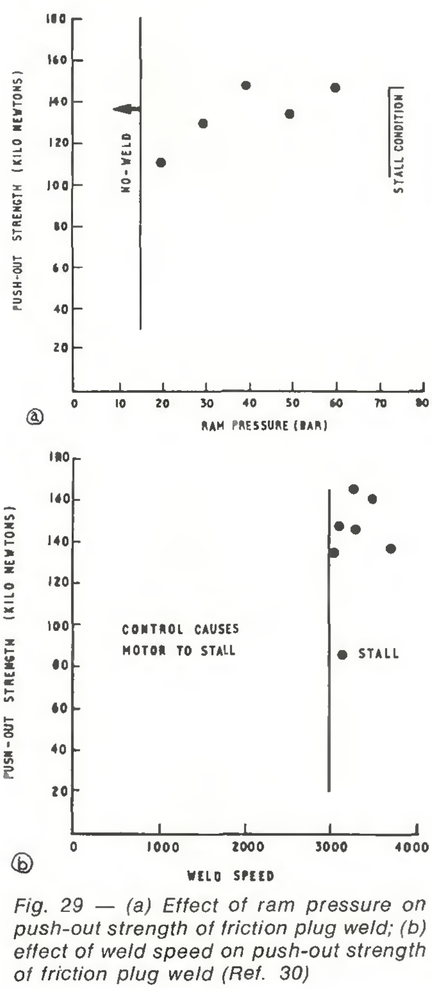


Fig. 29 — (a) Effect of ram pressure on push-out strength of friction plug weld; (b) effect of weld speed on push-out strength of friction plug weld (Ref. 30)

requirements imposed to achieve the safety demands.

Other repairs to reactor primary circuits accomplished in the UK have been to the 1.5 m diam bellows in the Berkeley CO_2-cooled nuclear power station (Ref. 29). The units consist of mild steel end rings with a 1Cr-¼Mo corrugated section (Fig. 27), cracking running up to 170 mm around the circumference being found to arise from the root through the HAZ of the weld metal/ring interface due to fatigue caused by continued flexing of the bellows. Such cracks do not lead to mechanical failure but they must be repaired to avoid gas leakage. Speed of repair is imperative because of the high cost of outage, and it was desirable to fill the 3 mm deep weld preparation in one pass, which is not really practical with the available GTAW processes. Gas metal-arc welding with CO^2 shielding was therefore chosen, as it is a one-handed process when used manually.

Since defects could arise at any point on the circumference of the bellows, welding was required in all positions and it was desirable for these to have common conditions. Therefore the short-circuiting mode was chosen in preference to spray transfer. The change in section at the weld required special measures such as low frequency pulsing, to avoid excessive heat buildup and 'burn through' of the thinner section. It was found possible to achieve this by intermittently interrupting the wirefeed, by cutting the current supplied to the wirefeed motor at appropriate intervals, care being taken to ensure that the dynamic braking of the motor was unaffected. A frequency of 1 Hz was found to give satisfactory welds with a continuous torch movement at about 180 mm/min. The power source to the electrode was kept connected at all times so that when the wire feed was stopped, the wire burned back until the arc was extinguished because of the limited available open circuit voltage. Restarting the feed short circuited the wire to the weld pool and restarted the weld. It is necessary to have sufficient protrusion of the wire from the nozzle to make sure the wire does not burn back so far that it welds to the contact tube.

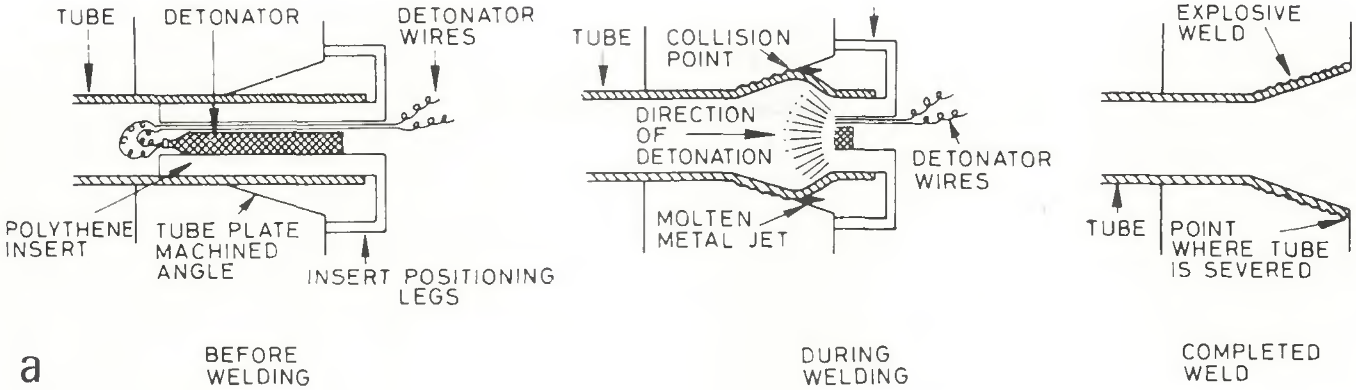
Because of the large number of boiler tubes, the speedy repair of heat exchangers containing leaking tubes, whether arising from tube corrosion or weld faults, has been the subject of considerable development. Such repairs usually are achieved by welding sealing plugs into the suspect tubes. One process used on CEGB power plant involves friction welding (Ref. 30).

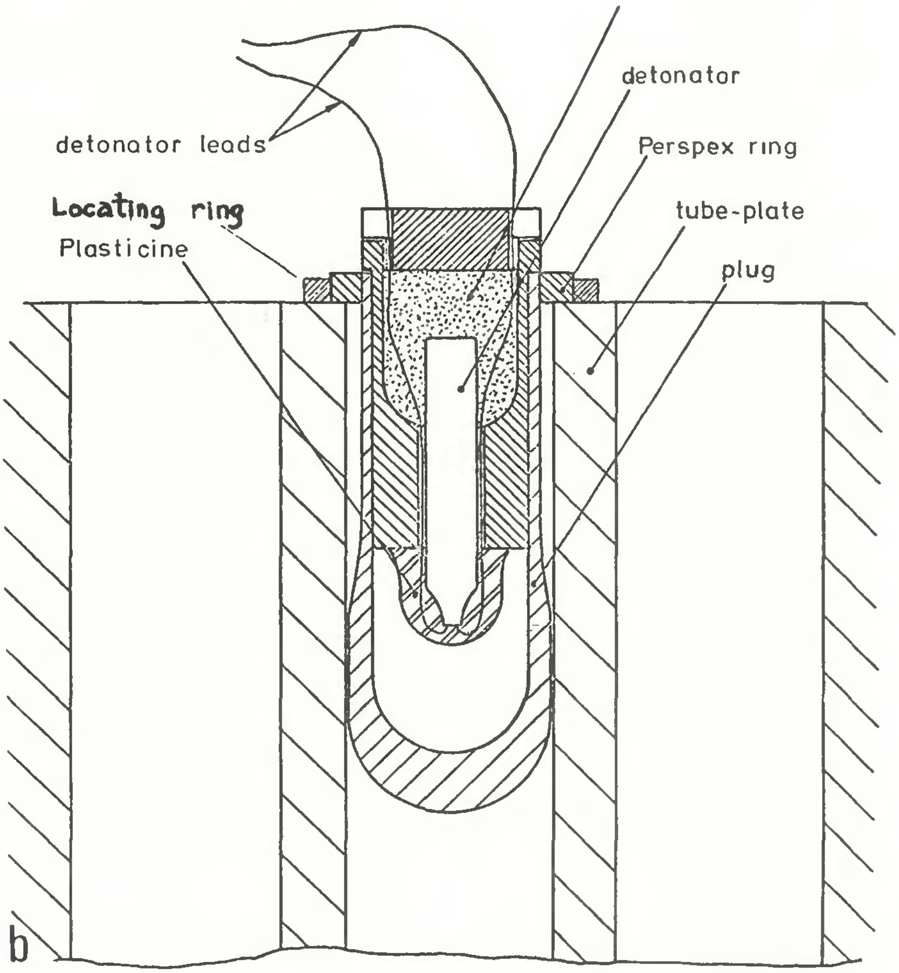
It was required to plug off holes in a header only 400 mm diam and 1.8 m long, access being provided from the end of the header by a 230 × 300 mm elliptical hole, itself reached through a 400 mm diam hole in the outer pressure vessel (Fig. 28). Access restrictions prevent the use of manual welding, the preparation for explosive welding, or precise pre-machining and GTA welding. Friction welding appears the most attractive choice and laboratory work was used to establish the parameters.

A friction welding machine was then designed at MEL which incorporated an hydraulic power drive and ram system to get sufficient power and force into a suitably small package. A framework which can rotate and move laterally is supported on a tubular section from each end of the header and carries the hydraulic motor, hydraulic ram, burnoff and speed transducers and reaction foot. The hydraulic and electric leads are taken out of the header through the tubular section, hydraulic energy being supplied from an external 20 litre, 280 bar storage unit, topped up by a 1.2 kW electric motor and pump. Because of the lightness of the rotating parts of the hydraulic motor, conventional control was not effective, and it was found suitable to connect the full pressure of the accumulator to the motor with the welding plug in position and preloaded, regulating the initial load and the axial advance of the plug (i.e., controlled burn-off).

Since NDT was impossible it was desirable to make sure the weld conditions gave an acceptable weld strength, or that significant deviation from these conditions produced recognisable stalling which could then lead to plug removal and rewelding. Push-out tests showed that this was achieved (Fig. 29) and a big advantage was that it could be achieved in a broad range of conditions and variations in shape at the hole to be plugged (Table 6).

In recent years explosion welding has been used in the nuclear industry for repair purposes chiefly for plugging operations in heat exchangers and similar plant. Apart from being suitable for all engineering materials and permitting the use of ductile plugs, e.g., made from high nickel alloys, the operation can be carried out in regions of restricted access which would preclude fusion joining methods. It also provides a welded joint capable of examination by ultrasonics and, for plugs on the face of a tube plate, an absence of crevice can be effectively checked by dye penetrant inks. The geometry of the plug can be varied to suit conditions, for example, to limit the length of plug or avoid damage to the ligament between holes. Typical plug





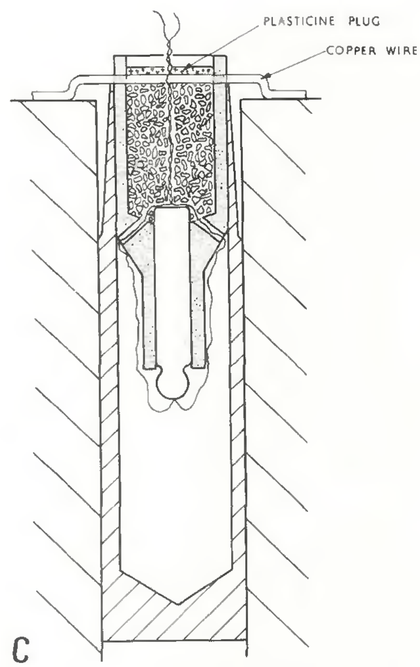


Fig. 30 — Some typical designs for explosion welded tube plugs. (a) after Hardwick (Ref. 31); (b) after Crossland and Bahrani (Ref. 32); (c) after Dickinson

types are illustrated in Fig. 30, and all can provide a crevice free joint by virtue of the plug end being cut off during welding. The main parameters to be controlled are: (a) charge weight, (b) disposition of the charge and transmission medium, (c) surface finish, (d) stand off distance or angle of taper, (e) plug clearance in the hole.

It is usual to select the joint design and to arrive at the required combination of these welding parameters by experiment on simulations of the particular geometries and materials involved, examining the procedure test assembly by ultrasonics, dye penetrants, metallography and mechanical tests. With appropriate conditions, push out tests will lead to failure in the plug body rather than in the weld, and leak tightness by helium mass spectrometry should indicate the joints are tight to at least 10^{-8} torr litres/sec.

Concluding Remarks

The examples in this paper have been chosen to indicate the importance of considering the implications of reliability of the product at all stages in design, fabrication and operation of a welded component. In the past selection of welding process has often been done primarily in terms of availability or first cost. Such cost differences are minute compared with the costs of outage and of a difficult repair. Economic common sense, as well as safety considerations, mean that for nuclear plant the prime reason for selection of a particular material, joint design or welding process should be that it will produce the most reliable result.

The shortage of comparative statistics on the defect-propensity of different welding procedures applied to particular joint configurations or of the relative effectiveness of different nondestructive examination techniques should be remembered; the International Institute of Welding may provide an appropriate organisation for collecting such data. The use of continuous procedural control with monitoring and feedback of welding conditions provides considerable advantages in many cases, whilst in all cases inspection aimed at establishing fitness for purpose is essential. The continued development of these techniques may be expected to give continued improvement in the assurance of reliability of welded structures, so important to nuclear power engineering.

Acknowledgments

I would like to express my appreciation for the friendly cooperation and helpful discussions with many welding enthusiasts around the world. In particular I wish to thank Dr. D. R. C. Anderson (Nobel Explosives, ICI Ltd); Professor Y. Ando (Tokyo University); Dr. F. Burdekin (Sandberg Ltd); Mr. F. Dickinson (UKAEA Eng & Mats Lab Risley); Mr. Gifford (International Combustion Division, Clarke Chapman Ltd); Monsieur H. Granjon (Institut de Soudure Paris); Mr. I. Hamilton (Babcock & Wilcox Operations Ltd, Renfrew Scotland); Messrs. P. Houldcroft, E. Fuchs, and J. Harrison (The Welding Institute, Abington, UK); Dr. A. Pritchard (AERE Harwell); Dr. S. Sato (Mitsubishi Heavy Industries Ltd, Tokyo); Mr. Tenze (Norske Veritas, Norway); Professor Vinkier (University of Ghent); Mr. D. White (UKAEA Reactor Fuel Laboratories Springfields); Messrs. L. Wyatt, Price and Boughton (CEGB HQ and Marchwood Laboratory) for allowing to quote from their results often before they have themselves published them. I thank also Mr. R. V. Moore, Member for Reactors, UKAEA, for his continued interest in the nuclear application of welding technology and for permission to contribute this paper.

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