Toward Better Standards for Field Welding of Gas Pipelines

A comparison of British and API standards presents a new point of view on acceptance criteria

BY R. F. LUMB AND G. D. FEARNEHOUGH

Introduction

Failures in gas pipelines operating at high pressure are rare, and in these failures, a girth weld is rarely responsible. An analysis by Battelle Memorial Institute of data (Ref. 1) shows that 9% of failures during hydrostatic testing and 7% of operational failures originated from girth welds. Furthermore, the majority of these failures were leaks rather than complete fractures (i.e., breaks). Similar statistics can be derived from reports issued by the United States Federal Power Commission (Ref. 2) and the Independent Natural Gas Association of America (Ref. 3).

Installation of major pipelines for transmission of gas at pressures up to 6.895 MPa (1000 psi) began in the UK in the early 1960's and since then some 12,000 km (7,500 miles) have been commissioned. During this time no service failures attributable to girth welds have occurred. There have been 6 failures during the commissioning-hydrostatic test, 4 resulting in leakage only, the other 2 being breaks. Both breaks were at girth welds between pipes and hot formed bends.

Pipelines transmitting high pressure gas through densely populated countries such as the UK are in close proximity to the general public. Hence the consequences of failure can be particularly severe and high construction standards are required. At the same time, costs must be controlled so that transmission of gas is economic. This paper aims to put girth weld standards in proper perspective, and considers approaches to welding procedures, quality control, quality assurance and acceptance standards for ensuring economic achievement of the correct standards.

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Pipeline Welding

The most economic welding for pipeline girth welds is the technique in which a covered electrode is moved around the circumference from the top to the bottom of the pipe. Fast deposition rates are possible. In order to prevent the natural tendency of the slag to run down the weld preparation ahead of the weld pool, the slag must have a high viscosity. Electrode coverings which lead to such slag properties are almost universally based on cellulose $(C_6H_{10}O_5)_x$. Cellulosic electrodes release large quantities of hydrogen to the weld pool, and this hydrogen can lead to a characteristic type of cracking, commonly referred to as root underbead cracking, Fig. 1.

In welding, high arc currents and deposition rates tend to lead to undercutting of the groove faces, and on the first and second passes it can be difficult to blend out. These undercut areas trap slag and lead to a characteristic defect commonly referred to as "wagon tracks," Fig. 2. If the fit-up and welding on the first pass are not balanced, the root opening may close thereby preventing penetration, Fig. 3. The wide manufacturing tolerances and distortion of pipes during transit and storage can prevent alignment of the two pipe ends, resulting in a defect commonly known as "mismatch" or "offset," Fig. 4. Other defects — piping, porosity, incomplete interpass or side wall fusion, randomly dispersed slag — are general welding defects and not a particular characteristic of pipeline welds.

Stresses Acting on Pipeline Girth Welds

In assessing defect significance in girth welds it is necessary to consider both the fracture mechanics aspects of defect stability and service experience with pipelines. Reference to experience is necessary since it is not always possible to define precisely the forces acting on a girth weld in service.

The longitudinal stress acting on girth welds during service is generally small. The major stress component arising from the action of internal pressure is derived from the Poisson contraction in the longitudinal direction due to expansion in the hoop direction, thus

$$\sigma = 0.3\ P \cdot r/t$$

where r is the pipe radius, t is the wall thickness and P is the operating pressure.

Consequently, even pre-service hydrostatic testing to yield stress levels does not result in high longitudinal stresses. Additional stresses oc-

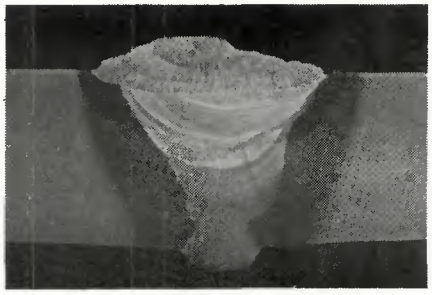

Fig. 1 — Root underbead cracking; X3, reduced 64%

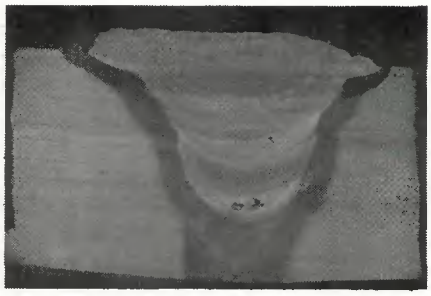

Fig. 3 — Inadequate root penetration; X5, reduced 64%

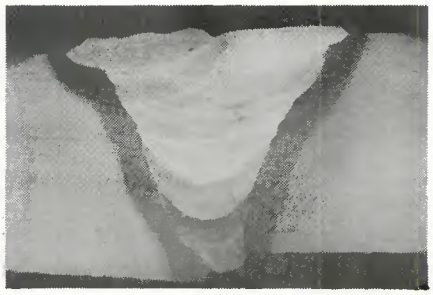

Fig. 4 — Root underbead cracking associated with a mismatch of pipe joint edges; X4, reduced 64%

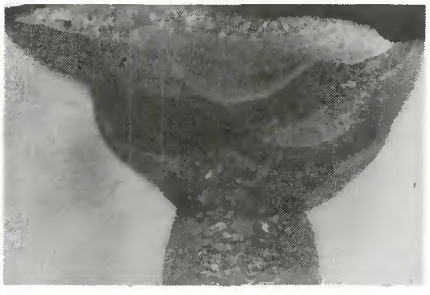

Fig. 2 — Slag entrapped by undercut groove faces. Radiographs often reveal the defect as parallel lines called "wagon tracks"; X5, reduced 64%

cur near bends and have been a contributory factor to hydrostatic test failures in the UK. Ground movement exerts additional longitudinal stresses, but again they are of restricted magnitude because shearing strains in the soil absorb some of the ground movement. Measurements on a German oil pipeline (Ref. 4) indicated longitudinal stresses to be well under 0.5 yield stress. Nevertheless, the possibility of higher longitudinal stresses in subsidence areas cannot be discounted and it is reasonable to define defect significance in terms of the development of longitudinal stresses equal in magnitude to the specified minimum yield stress of the pipe. Under those conditions the parent pipe material would absorb the majority of the strain, particularly when account is taken of overfill and overmatching of the yield strength of the deposited metal in the girth weld.

Fatigue is a consideration in pipelines line-packed to provide storage. However, the resultant longitudinal cyclic stresses are again small and not significant.

Failure Criteria

Types of Failure

Definition of the stresses acting on girth welds permits definition of the consequent deformation at the tips of defects. The significance of defects depends on how the weldment reacts to these deformations. In doing this it is necessary to distinguish between two failure modes. An initially stable defect may grow due to either increasing pressure, pressure cycling, or under the influence of steady pressure, to cause eventual failure. This can be termed ductile fracture and may be a leak or break. Alternatively, a defect may suddenly extend in a brittle manner generally resulting in a break, though a leak is conceivable if early fracture arrest occurs within the weld metal.

Brittle Fracture

Fracture initiation from a defect occurs when, in fracture mechanics terminology, the crack driving force exceeds the material's fracture toughness.

The most appropriate way to assess initiation in pipelines is on the basis of general yielding fracture mechanics. This concept relates to the displacement, δ_a (commonly referred to as Crack Opening Displacement, or COD) which is generated at the tip of a crack of size a, when the crack is subjected to an applied stress σ, i.e.,

$$\delta_a = f(\sigma, a)$$

Analyses of defect significance (Ref. 5), have led to a relationship between δ_a generated at the tip of a crack, applied strain ε, yield strain ε_y and equivalent defect size a:

$$\delta_a/(2\pi\varepsilon_y\bar{a}) = \varepsilon/\varepsilon_y - 0.25, \text{ for } \varepsilon/\varepsilon_y \geqslant 0.5$$

The applied strain is the total of contributions due to design forces, residual stresses and stress concentrations.

As an example, consider a 3 mm deep defect (25% of a 12 mm wall thickness pipe) in material to AP15LX60 (yield strength 4×10^8 Pa) subjected to a longitudinal stress close to the yield stress; the COD, δ_a would be 0.03 mm. This COD relates to the tip of an embedded center wall defect, but for defects nearer the free pipe surface the COD increases. For a surface breaking defect it can be twice that of an equivalent centerline defect.

It is evident, therefore, that defects in girth welds generate small but finite displacements at their tips. It is now necessary to establish whether such displacements can cause fracture. Fracture cannot occur if the toughness of the weldment is sufficiently high that the crack tip region is capable of withstanding this displacement, i.e., if the COD required to give fracture initiation, δ_c, exceeds the COD δ_c generated at the crack tip. A direct determination of δ_c is obtainable from a COD test (Ref. 6), in which a specimen containing a defect simulating a weld defect is bent to failure, allowing the defect displacement at failure, δ_c to be recorded. An analysis of a wide range of manual metal arc mild and low alloy steel weld metal deposits (Ref. 7) has shown that fracture initiation at 0 C occurs at δ_c levels greater than 0.1 mm; i.e., significantly greater than the δ_a value generated at the tip of a 3 mm deep defect in a girth weld. Consequently fracture initiation would not be expected from relatively large (25% wall) defects.

While it may not be appropriate to assume high toughness levels in all existing weld metal deposits, it is certain that the intrinsic brittle fracture resistance of multipass weld deposits is a primary factor accounting for the rarity of girth weld failures. However, the degree of tempering of the heat-affected zone by the deposition of multipass weld deposits may not be adequate to impart toughness to the heat-affected zone matching that of the weld metal. Girth weld failures have been attributed to the inability of the heat-affected zone to resist propagation of root underbead cracking. Root underbead cracking is to some extent indicative of poor weldability with concomitant low heat-affected zone toughness. Although it is feasible theoretically to define acceptability of root underbead cracks on the basis of fracture mechanics, it seems advisable for the present to treat all such cracks with suspicion.

Ductile Fracture

Ductile failure of axially orientated defects in pipes has been interpreted on the basis of a plastic collapse mechanism, the criteria for failure being related to tensile properties. In partial wall defects the controlling parameter is a "flow stress" (an arbitrarily defined stress level between the yield and ultimate tensile stress) on the ligament (i.e., the remaining pipe wall). Data from actual failures and experimental burst tests from various sources are collated in Fig. 5, where the failure stress/specified minimum yield stress ratio (σ_f / σ_{smy}) is plotted against the ligament/original wall thickness ratio, r. The data were analyzed according to the formula

$$\sigma_f / \sigma_{smy} = A \cdot L \cdot r$$

where A is a constant, and L another constant dependent on defect length. Statistical analysis showed that the 95% lower confidence limit of the constant A × L is 1.315 and this value is shown on the figure. To account for time dependent effects, the constant has been reduced by a factor of 5% to derive A × L = 1.27. This criterion is satisfactory for all materials unless some form of easy ductile crack extension occurs (Ref. 8).

If the tolerance to longitudinal stresses of yield point magnitude is considered in terms of Fig. 5, it can be seen that a defect of depth close to 20% wall thickness is tolerable. Therefore large amounts of porosity and piping can be tolerated. Defects associated with individual weld passes, e.g., inadequate root penetration, incomplete interpass fusion, distributed slag, wagon tracks, can be tolerated in large amounts provided the weld procedure adequately restricts the radial dimensions of individual passes.

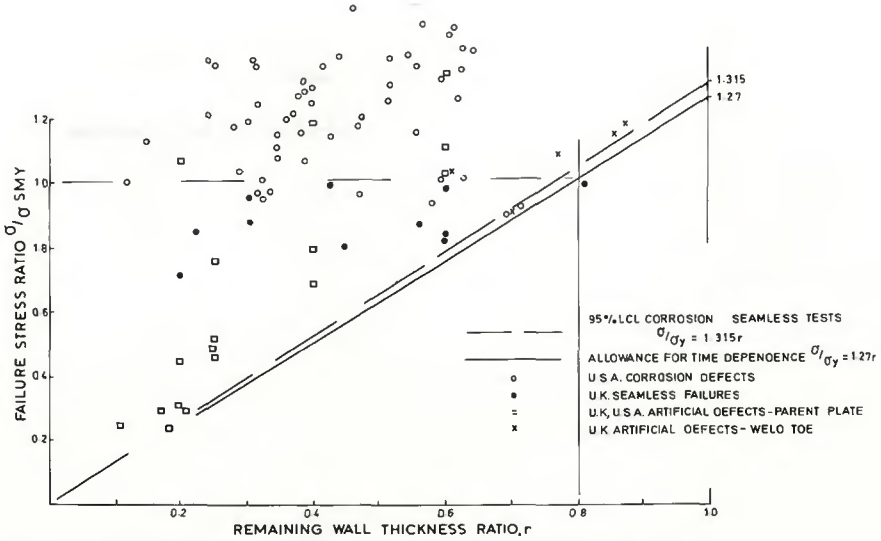

Fig. 5 — Influence of remaining wall thickness on failure stress ratio

Root Underbead Cracking

Although root underbead cracking usually accounts for very few of the weld repairs carried out in practice (one or two per cent would be regarded as a high incidence) the analysis in the previous section indicates that it is the only really severe defect. Therefore it is pertinent to consider in further detail how it is caused and how its incidence might be reduced or eliminated. Root underbead cracking can occur when the following conditions prevail (Ref. 9):

1. Presence of a sufficient level of hydrogen,
2. Existence of a susceptible microstructure (martensite),
3. Presence of (1.) and (2.) while the temperature of the steel falls below 200 C, and
4. Strain on the weld.

With covered electrode welding (as described earlier) hydrogen cannot be avoided, but fortunately the presence of hydrogen per se does not cause root underbead cracking. This has led to root underbead cracking sometimes being referred to as hydrogen assisted cracking.

Procedures minimizing or eliminating combinations (1.) (2.) and (4.) have been investigated at the British Gas Engineering Research Station (Ref. 10). The increasing use of higher yield strength, thicker walled pipes has increased the problem. The strength of steel can be increased in many ways, one common method being to increase certain alloying elements. With increasing alloying, the carbon equivalents may exceed the recommended maximum for welding without preheat*. The carbon equivalent of current thick walled pipes to API5LX60 are near to or above the generally accepted limit. Some degree of preheating is advisable, both for this reason and to offset the high cooling rates obtained with such pipes. In addition to reducing the cooling rate, which itself reduces susceptibility to martensite formation, preheating also helps to prevent the partly finished weld from passing into the critical temperature range below 200 C.

Mechanical stress can be applied inadvertently to the weld in handling the pipe and in trying to accommodate mismatch and misalignment at the butting surfaces. These stresses, acting on a partially completed or even completed root run,

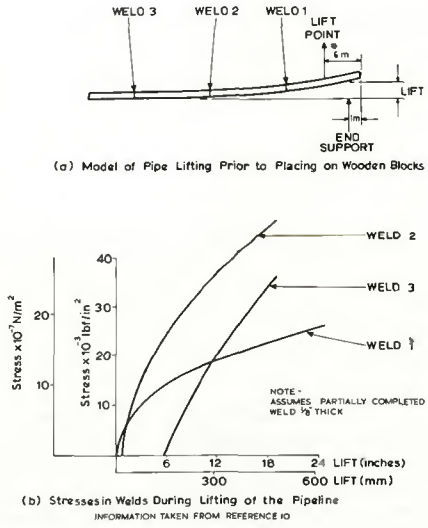

Fig. 6 — Effect of lifting pipe

can cause high strains. Both sources of strain increase with pipe wall thickness. Stresses due to accommodating the mismatch and misalignment resulting from pipe ovality, longitudinal weld face topping and differences in diameter are developed as the pipe attempts to revert to its original shape when the clamp is released and can be expressed as: stress $\propto (t/r)^{3/2}$, where t is the pipe wall thickness and r the radius. Handling stresses are probably of much greater magnitude, and can be appreciated from Fig. 6 which illustrates a part of a pipeline on supports. If the free end is lifted, the maximum stress (which occurs at weld 2) is given by:

$$\sigma \propto c(t/w) \sqrt{h}$$

where c is a stress concentration factor due to the geometric notch at the partially completed weld, t is the wall thickness, w is the thickness of the

**The maximum carbon equivalent (CE) for welding without preheat is a matter of contention. Defining CE as = C(%) + 1/6 Mn (%), maxima of 0.42 for 12.7 mm (0.50 in.) pipe and 0.39 for 16 mm (0.625 in.) pipe have been suggested (Ref. 9).*

weld deposition at the time of lift, and h is the height of lifting. Stresses for an X60 pipe 915 mm (36 in.) diam by 16 mm (0.625 in.) wall are shown in Fig. 6. To obtain peak tensile stress at the outer surface of the weld/heat-affected zone the stresses should be multiplied by c = 3. Thus yield point stresses result at weld 2 from a lift of 15 cm (5.5 in.). The maximum stress occurs at the 12 and 6 o'clock positions, and there is statistical evidence that a preponderance of cracks occur at these positions.

Large diameter pipes, being heavier, cause greater handling problems, and additional strain may result from movement of cranes, slings, etc, when maneuvering the pipe. Where cracking might be anticipated it is provident for weld procedures to specify minimum quantities of weld to be deposited before lowering off the slings and removing clamps and also to put limits on the permitted lifting.

Even when the aforementioned precautions are taken into account, it is still pertinent to question whether the pipe as supplied by the mill can be welded without incidence of root underbead cracking. Reliance on chemistry per se is not adequate. The approach adopted by British Gas Corporation is to require the pipe manufacturer to demonstrate weldability by welding together 2 full lengths of pipe under strictly defined conditions (Ref. 11). Freedom from root underbead cracking must be achieved.

When considering long term solutions to the problem, the most attractive is to eliminate the hydrogen. For pipelining. CO_2 welding is potentially the best low hydrogen welding technique. Although manual CO_2 welding was tried on gas transmission lines in the UK in the early 1960's, the first successful application was in the late 1960's (Ref. 12).

CO_2 welding, being a low heat input process, is more prone to incomplete interpass and incomplete side wall fusion defects than is the higher heat input manual metal-arc welding. Correct choice of parameters, more rigidly controlled than in manual metal-arc welding, is necessary to avoid incomplete fusion defects. The recent performance of automatic CO_2 welding on a major gas transmission line in the UK indicates that these requirements can be satisfied (Ref. 13).

Quality Control

The most widely used specification for field welding of pipelines is API 1104. From consideration of the foregoing discussions of failure and underbead cracking and other considerations in this and the following sections, it is evident that in some respects an alternative philosophy is appropriate.

Weld Procedures

The objective of weld procedure qualification is to demonstrate that, provided the weld does not contain defects outside the acceptance standard, its performance will satisfy service requirements. While it is necessary to ensure that the procedure is such that welders can perform adequately, the objective is primarily a confirmation of mechanical properties. API 1104 requires the procedure weld to be examined destructively employing the following tests: transweld tensile, nick break, root bend, and face bend.

The nick break test reveals the presence of defects in the fracture face, but gives no indication whether the defect length is within specification or not. It is pertinent to question whether defects would not be more effectively quantified by nondestructive testing. The function of the bend test is often confused. It is generally accepted that it (1) reveals defects in the weld metal and (2) provides a measure of weld metal ductility. If a test is to perform two separate functions, there must be no interaction between them. As has been pointed out (Ref. 14), this condition is not satisfied in the bend test. Many bend tests have failed due to initially small defects within the acceptance standards, whereas retests at an initially defect free region of weld withstood the test. Hence interaction between ductility and defects is unavoidable and neither is quantified satisfactorily.

Given that defects can be revealed in nick break tests and by nondestructive testing, the requirement is for a measurement of weld metal ductility. An unambiguous assessment of ductility relevant to defect tolerance can be made by the COD test. Unfortunately, there are practical problems in implementing COD tests on a routine basis, but fracture toughness as measured in a Charpy V-notch test can be an effective guide. It has been shown that there is a relationship between Charpy energy and COD (Ref. 7), a COD of 0.15 mm corresponding to Charpy energy of 26 J. It is evident that a Charpy value of about 26 J provides an adequate level of brittle fracture resistance since the equivalent COD exceeds that generated at the types of realistic girth weld defects δ_a (as discussed previously). Where toughness cannot be determined directly, such as at heat-affected zones, a measure of toughness can be inferred from hardness measurements. High hardness per se is undesirable due to the possibility of hydrogen (released by cathodic protection systems) being absorbed by hard areas and leading to embrittlement and possible cracking.

Taking account of these considerations the British Gas Corporation Specification for Field Welding of Pipelines* assesses weld procedures on the basis of nondestructive testing and macro examination, Charpy 'V' notch tests, transweld tensile tests, and hardness tests.

Welder Qualifications

The objective of welder qualifications is to confirm that the welder can produce a weld with the specified freedom from defects; i.e., defect level directly attributable to welder competence is the only criterion for deciding qualification. Defects which can be attributed to inadequacies in the procedure are not a reason for rejection. API 1104 details mechanical tests for adjudicating welder qualification. However, the objective can be investigated without recourse to mechanical tests of any kind, and adjudication by nondestructive testing only is more appropriate. In the British Gas Corporation Specification, welders are qualified on the results of nondestructive tests only.

Quality Assurance

Definition of Requirements

For pipelines transmitting gas at high pressure through densely populated countries, assurance of weld quality is imperative. As even high level hydrostatic tests only impart low level longitudinal stresses on the girth weld, proof testing alone is not adequate. Hydrostatic tests must be complemented by nondestructive testing. It is seen from previous discussion that detection and reliable identification of root underbead cracking is of paramount importance, whereas considerable latitude exists with regard to the ability to detect other defects unless extremely gross.

Although API 1104 permits examination of a proportion of welds, the incidence of root underbead cracking is predictable. Therefore it is difficult to support any philosophy other than 100% inspection, or at least inspection of all welds at the 12 and 6 o'clock position. The British Gas Corporation Specification requires 100% nondestructive testing on all welds in pipelines operating at pressures exceeding 0.69 MPa (100 psi). It now remains to select the most appropriate nondestructive testing technique. Magnetics, ultrasonics and radiography are available and have

*BG/PS/P2

been discussed in detail in the context of examining pipelines (Ref. 15).

Magnetic Methods

Root underbead cracking breaks the internal surface of the pipe, and is thus amenable to surface crack detection. Either dye penetrants or magnetic particle methods are available, but as the magnetic particle method is more tolerant of surface finish and cleanliness and is less open to abuse, it is preferred. The magnetic particle method requires access to the inside of the pipe and therefore can only be applied to pipelines of 30 in. (0.76 m) diam or greater. However detection is reliable and interpretation is not a problem except for occasional confusion from sharp changes in root profile causing indications similar to shallow cracks. Where applicable it provides the most reliable method of ensuring freedom from root underbead cracking, and is a mandatory requirement of the British Gas Corporation Specification. Magnetic crack detection has been applied from the outside surface of pipe in Russia (Ref. 16), the variations in magnetic field being recorded on tape.

An assessment of this type of equipment at British Gas Engineering Research Station showed that, although the test is more sensitive to defects at or near the outside surface, it still has inherent potential for the detection of defects at the inside surface. However, when used on welds, the varying root penetration complicates the magneitc field to such an extent that the identification of root underbead cracking is not possible. Figure 7 illustrates this point.

Ultrasonics

In ultrasonic testing of welds, defects are discriminated by accurate positioning of the source of the defect echo, preferably during scanning from more than one direction. The most skilled of operators might be able to gain additional information on defect type from the shape of the echo on the oscilloscope screen, but the quality of display on battery operated flaw detectors used in daylight is not sufficiently distinct for this latter facility to become general pipeline practice.

The more significant defects occur in the root of the weld, where discrimination between sources of echo reflection is most difficult. Perfectly acceptable geometric features such as high-low or certain shapes of root penetration cause echoes of comparable magnitude to those from root underbead cracking or inadequate joint penetration. Hence discrimina-

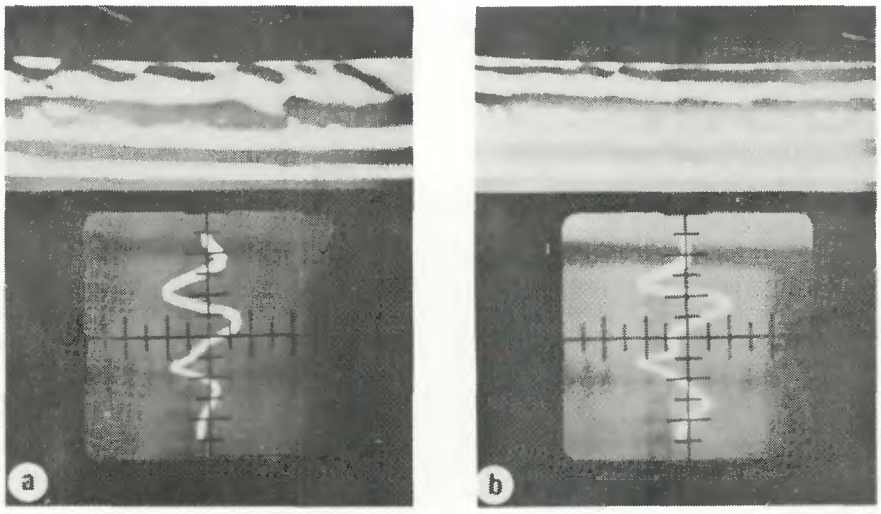

Fig. 7 — Magnetographic indications on pipeline girth weld. (a) Trace from part of weld having root underbead cracking; (b) trace from part of same weld but in defect-free region

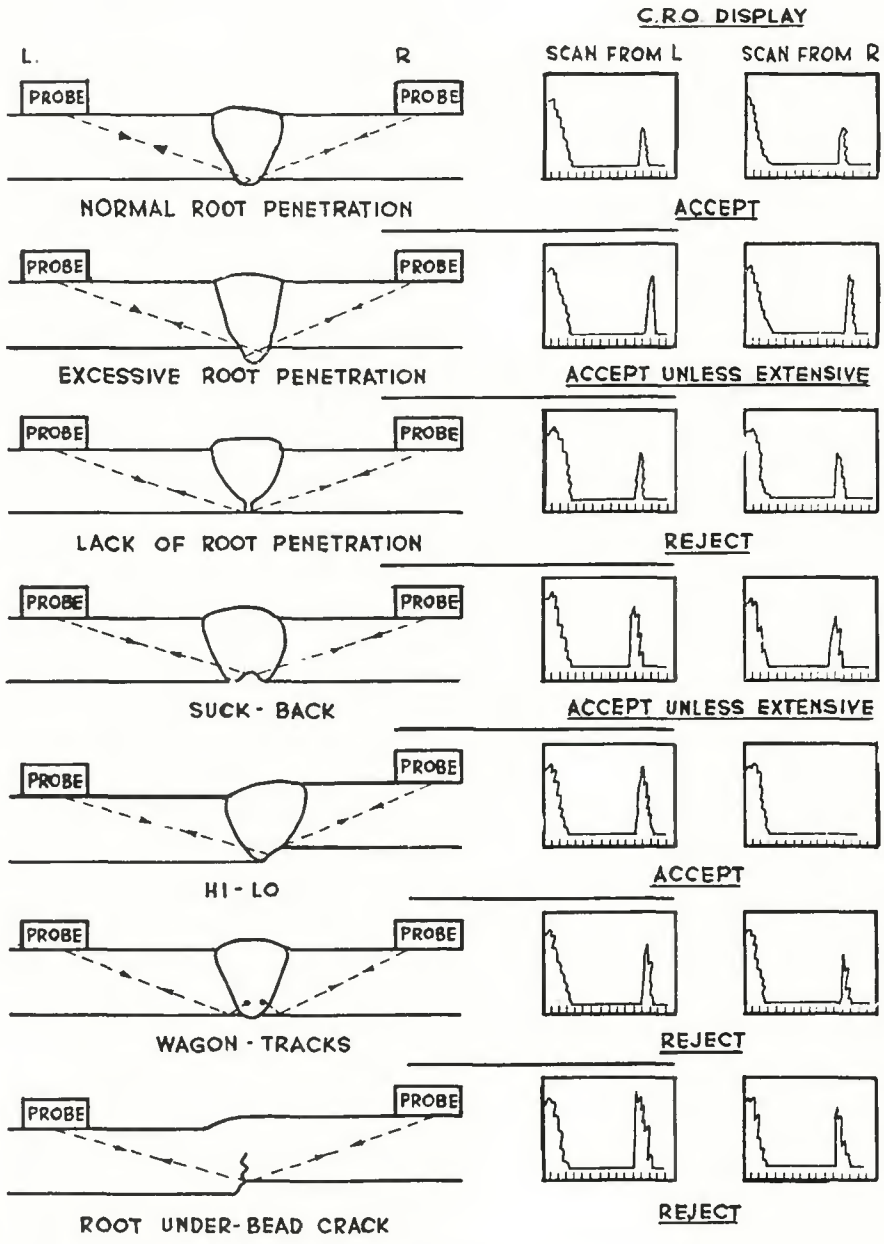

Fig. 8 — Interpretation of echoes from weld root

tion from positioning is very critical, as illustrated in Fig. 8. The differences in beam path length are small and precise location of the probe with respect to the weld centerline is necessary.

These stringent demands on the operator must be considered in the context of the pipeline environment. Even if the probe location is indicated by pre-marking the pipe, as has been suggested (Ref. 17), it is difficult for an operator to site accurately a probe in the overhead position, while at the same time being himself in such a posture to permit accurate viewing of the flaw detector oscilloscope. It is unrealistic to expect that an operator can maintain a high degree of competence in implementing such tests over long periods of time in adverse terrain and/or climate.

Ultrasonic testing has a useful function in assisting radiographic interpretation occasionally. However the technique is unsuitable as a primary nondestructive testing method and is not permitted for this purpose in the British Gas Corporation Specification. If and when effective ultrasonic systems with mechanized scanning and concomitant automatic recording of signals are developed, the role of ultrasonics can be reconsidered.

Radiography

Except for two dimensional defects such as root underbead cracking, inadequate joint penetration, and in CO_2 welding incomplete side wall and interpass fusion, the other defects in pipeline girth welds, being three dimensional are amenable to detection by radiography. Detection is possible even with poor technique and/or workmanship. Also, as indicated earlier, three dimensional defects have little significance unless severe. Hence they present no problems and need not be considered further.

Detection and reliable interpretation of two dimensional defects require good workmanship and optimum radiographic techniques. Assuming good workmanship, the quality of a radiograph depends on the choice of the parameters controlling its definition (unsharpness) and contrast. Detection and facility for correct interpretation of indications improve with increasing contrast and decreasing unsharpness.

Considering contrast initially, the most important parameter is the radiation energy. Absorption of radiation by steel decreases with increasing energy; the absorption coefficient at 150 kV being about 3 times that at 700 kV. For optimum detection of small changes in thickness (i.e., contrast sensitivity), the absorption should be as high as possible so that large differences in energy (consistent with a reasonable amount of energy being transmitted to provide a realistic overall exposure) result at the film. Gamma radiation from an Iridium 192 source is approximately equivalent to x-rays generated in the range 600-700 kV, and hence will not be absorbed sufficiently to give good contrast sensitivity.

For typical pipeline wall thicknesses, x-rays generated in the range 150-175 kV provide good contrast. Given correct technique, the minimum contrast requirement of API 1104 is not sufficiently demanding. The British Gas Corporation Specification requires contrast sensitivities of 1.5% with single wall, single image exposure and 1.8% with double wall, single image exposure, using DIN image quality indicators on the film side. Such sensitivity cannot be achieved with gamma rays from an Iridium 192 isotope.

Various proprietary films are used in pipeline radiography. Differences in contrast performance between proprietary films, and between medium speed and fine grained categories of film, are small and the choice and state of developer is probably of equal or greater consequence. Contrast increases with film density, and in a typical medium speed film contrast increases by 50% on increasing the film density from 1.5 to 3.0. Radiographic viewing screens are usually suitable for densities up to 3.5 and radiographic density should be specified to utilize fully this range. A higher minimum density than that specified in API 1104 would be more appropriate, and a value of 2.5 is stipulated in the British Gas Corporation Specification.

Now considering definition, detection of defects, and even more particularly correct identification of defects from their radiographic image, requires that the delineation of the image be sharp. There are three sources of unsharpness: (1) the well known geometric unsharpness U_g resulting from the finite size of radiation sources, (2) unsharpness in the film U_f resulting from the kinetic energy of the radiation, grain size of the emulsion and degree of development, and (3) the unsharpness resulting from the screen U_s. The contribution of the three sources to the total unsharpness U_t is:

$$U_t = (U_g^3 + U_f^3 + U_s^3)^{1/3}$$

where

$$U_g = S_s \times O_f / (S_f - O_f),$$

and S_s = source size, O_f = object to film distance, and S_f = source to film distance.

Source sizes are typically 2 mm, hence it can be appreciated that in pipeline radiography U_g is less than 0.1 mm even in panoramic exposure. The kinetic energy of the radiation has a pronounced effect on U_f since the radiation liberates secondary electrons from the silver halides in the emulsion. High energy imparts sufficient energy to the electrons to enable them to reach the adjacent grain rendering it developable, thereby spreading the image. For example at 175 kV or less U_f is about 0.01 mm whereas at energies equivalent to Iridium 192 it is about 0.12 mm (Ref. 18). If conventional lead screens are used U_s is negligible. Hence, as with contrast, the radiation energy is the most important parameter. It is evident that gamma rays from an Iridium 192 isotope increase U_t significantly compared with x-rays.

Recently a proprietary fluorometallic intensifying screen has become available* which when used with some proprietary films permits a reduction in exposure of up to x 10, without loss of contrast (Ref. 19). Such reductions are highly desirable when employing double wall, single image (DWSI) exposure. There is a small increase of about 0.05 mm in U_t, which is tolerable.

In addition to the importance of minimizing unsharpness to facilitate recognition of defect images, there is an interaction between U_t and contrast. If U_t is greater than the width of the flaw (and with cracking it usually will be) the contrast is reduced in proportion to the ratio U_t/width of flaw. It can be appreciated that unsharpness is a most important parameter in radiography. Maximum permitted values are rarely quoted in specifications, possibly because the image quality indicators available for measuring unsharpness (Ref. 20) are not yet accepted universally.

An appreciation of the relative performance of gamma and x-radiography is presented in Table I. From this it can be seen that the root underbead cracking in Fig. 1, while detectable and easily recognizable with x-rays, cannot be discriminated with gamma rays. The lack of penetration in Fig. 3 is barely detectable with gamma rays. It is clear that x-radiography is superior to gamma radiography for pipelines, and that its use leads to a significantly greater probability of detection and correct identification of root underbead cracking. In the British Gas Corporation Specification, the use of x-radiation is mandatory; gamma radiation is not permitted.

Nondestructive Testing Practice

Rationalization of the nondestructive testing of pipeline girth welds reduces the problem simply to that of

Kyokko Type SMP 303

Table 1 — Radiographic Technique and Effect on Defect Detection

Weld Details	Technique	Contrast DIN IQI,[a] %	Unsharpness, mm	Interpretation
A From 30 in. (760 mm) OD, ⅝ in. (15.87 mm) wall pipe, see Fig. 1	X-ray; panoramic exposure 150 kV.	1.75	<0.1	Root underbead crack 1½ in. (38.1 mm) long clearly visible.
	Gamma-ray; ^{192}Ir source; panoramic exposure.	Not measured; BWRA IQI 2.4%	0.175	Just visible when site of defect known; most severe interpretation: a shallow root undercut.
B From 30 in. (760 mm) OD, ⅝ in. (15.87 mm) wall pipe, see Fig. 3	X-ray; panoramic exposure; 160 kV.	1.25	<0.1	Lack of penetration clearly visible for 6 in. (152 mm)
	Gamma-ray; ^{192}Ir source; panoramic exposure.	2.1	0.172	Lack of penetration visible for 3 in. (76.2 mm). Fig. 3 section not detectable.
	Gamma-ray; ^{192}Ir source; double wall exposure.	2.8	0.170	Lack of penetration visible for ½ in. (12.7 mm).

(a) The image quality indicator (IQI) results are averaged from a number of radiographs on the same weld.

detecting and reliably interpreting root underbead cracking. The most suitable nondestructive testing technique is magnetic particle crack detection applied from the inside of the pipe, but it can only be implemented on large diameter pipes and even then the environmental conditions for the inspector are onerous. Hence it can only be considered as a most valuable supporting technique. The most suitable primary inspection is x-radiography applied to all welds. For large diameter pipelines constructed at reasonable rates, the x-radiography can be implemented relatively inexpensively and at a rate to keep pace with welding, by use of crawlers (Ref. 21). On small diameter pipelines and/or those constructed at slow rates, double wall single image exposure is the only procedure available at present, and a modest economic penalty compared with the cost of gamma radiography must be accepted.

Even when using optimum x-radiographic techniques, root underbead cracks can escape detection, examples being shown in Figs. 9 and 10. As indicated earlier, experience has shown that the incidence of cracks at pipe-to-fitting welds is greater than that at pipe-to-pipe welds. A desirable procedure is to weld short pipes to fittings prior to welding into the line, so that access to the root of the pipe-to-fitting weld is available even on smaller diameter pipelines, for magnetic crack detection of the weld.

Competence of Inspection

It is common practice for pipeline owning concerns to subcontract inspection during construction to a specialist organization. For example,

Fig. 9 — Crack 0.15 in. (3.8 mm) deep not detected by radiography

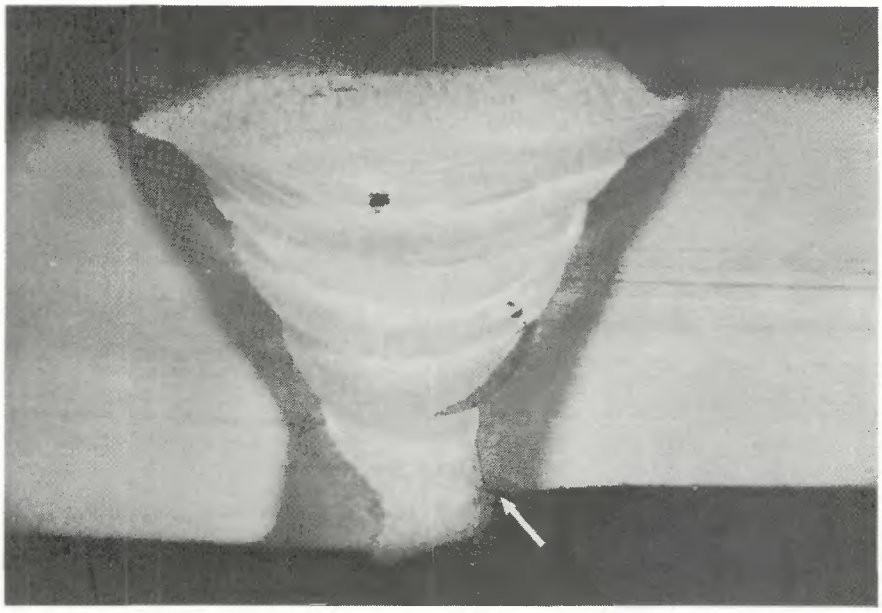

Fig. 10 — Crack not detected by radiography

British Gas Corporation has employed up to 700 subcontract inspection personnel during a year. A prerequisite of proper financially competitive tendering is that all organizations compete on the same terms. Where the principal content of the tender is expertise, there is a tendency to lower standards unless competence can be specified. Recognizing this tendency, British Gas Corporation introduced a competence certificate examination in 1968. The examinations are carried out at their Engineering Research Station, and have become known as the ERS Approval Scheme for Pipeline Inspectors. Since its inception, 1770 inspectors have undergone examination. It is a mandatory requirement that only personnel approved to appropriate grades in the relevant subjects can be employed on contracts for British Gas Corporation.

The examination, which is of specialist nature relating to pipeline girth welds only, incorporates written, oral and practical tests, with the emphasis on the latter. Subjects included in the examination are welding supervision (including mechanical tests on procedure girth welds), radiography (including radiation safety), ultrasonic testing, magnetic particle crack detection, cathodic protection, coating and wrapping, and knowledge of specifications. Comprehensive details have been presented previously (Ref. 22). Successful candidates are issued an identity card, appropriately endorsed.

Site policing is an integral part of the Approval Scheme. Visits to sites on a random basis are made during approximately 12 weeks of each year, and the performance of approved personnel monitored. As a result of this policing during the years 1968-71, 17 inspectors were downgraded and 8 had their approval withdrawn completely due to unsatisfactory performance or malpractice.

Acceptance Standards

As was stated at the beginning of this paper, failures in girth welds are rare. Since it would be naive to assume that this reflects particularly high girth weld quality on existing pipelines, it can only be deduced that girth weld toughness is relatively high and that levels of stress acting on them are insufficient to make existing defects significant. The theoretical considerations of failure discussed earlier support this interpretation of service experience. Obviously relatively severe defects can be tolerated, except for root underbead cracking.

It is important to note that, from fracture mechanics considerations, the depth of the defect is the only relevant parameter. Significance of defect calculations is based on defects of infinite length. However nondestructive testing techniques presently available do not permit quantitative estimation of defect depth. Length restrictions are therefore retained in specifications in as much as the length might be some indication of defect extent in depth and also of general standards.

API 1104 quite rightly permits a high level of defect, much greater for example than typical pressure vessel codes. There is an ignorance factor implied in API 1104 as neither 100% inspection nor optimum nondestructive testing techniques are required. It might be implied that, if they were, even further relaxation might be contemplated. Except for cracks, the British Gas Corporation Specification allows rather more extensive defect levels than are permitted by API 1104.

Conclusions

From consideration of the stress acting on pipeline girth welds, it is evident that large weld metal defects can be tolerated if adequate ductility is guaranteed. Adequate ductility can be obtained from consumables commonly used for pipeline welding. However root underbead cracking in the heat-affected zone of the weld is likely to be more significant. Quality control and quality assurance can therefore be rationalized to ensure elimination of this type of defect. It is British Gas Corporation practice to construct pipelines transmitting gas at high pressure to their own Specification, which incorporates significant amendments to the Speclification API 1104 used hitherto.

Welding procedures can best be qualified on the basis of a weld metal tensile test to ensure adequate strength, Charpy impact test and hardness measurements from macrosections to ensure adequate ductility, and nondestructive testing to ensure an acceptable level of defect. Welders can best be qualified on the basis of nondestructive testing only, as only their ability to weld according to the procedure and produce welds with an acceptable level of defect is in question. For pipelines transmitting high pressure gas through densely populated countries quality assurance nondestructive testing should be applied to all welds. The most suitable primary technique is x-radiography, as it is technically superior to gamma radiography and more reliable in practice than manual untrasonic testing, for the detection and correct identification of root underbead cracking. Where practicable on larger diameter pipelines x-radiography should be supported by magnetic particle crack detection applied from the inside of the pipe.

Provided that 100% inspection using optimum nondestructive testing techniques is implemented by competent personnel, some relaxation of the defect levels permitted by API 1104 can be considered.

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WRC Bulletin
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"High-Temperature Brazing"

by H. E. Pattee

This paper, prepared for the Interpretive Reports Committee of the Welding Research Council, is a comprehensive state-of-the-art review. Details are presented on protective atmospheres, heating methods and equipment, and brazing procedures and filler metals for the high-temperature brazing of stainless steels, nickel base alloys, superalloys, and reactive and refractory metals. Also included are an extensive list of references and a bibliography.

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WRC Bulletin
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"A Review of Underclad Cracking in Pressure-Vessel Components"

by A. G. Vinckier and A. W. Pense

This report is a summary of data obtained by the PVRC Task Group on Underclad Cracking from the open technical literature and privately sponsored research programs on the topic of underclad cracking, that is, cracking underneath weld cladding in pressure-vessel components. The purpose of the review was to determine what factors contribute to this condition, and to outline means by which it could be either alleviated or eliminated. In the course of the review, a substantial data bank was created on the manufacture, heat treatment, and cladding of heavy-section pressure-vessel steels for nuclear service.

Publication of this report was sponsored by the Pressure-Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 197 is $5.50. Orders should be sent to the Welding Research Council, 345 E. 47th St., New York, N.Y. 10017.