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Weld failures in sleeve reinforcements of pipelines

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Abstract

Based on fractographic, metallurgical, mechanical and fracture mechanics analyses, the causes of three failures in welded full encirclement sleeve repairs in a 24 in gas pipeline were evaluated. These failures were related to poor manufacturing procedures. The material used to build the sleeves was old and had poor transverse strength. High heat input cellulosic electrodes were used to weld the field joints, which lead to hydrogen embrittlement in the HAZ, also helped by relatively high circumferential stresses and defects of lack of fusion. A series of changes were introduced, including improvements in the in-plant fabrication and the in-field installation of the repair sleeves. A low hydrogen weld procedure with controlled penetration, NDE specifications and epoxy fillers were introduced to minimize the risk of sleeve failures and plastic collapse of the pipe.

Keywords: Pipeline failures; Fitness for purpose; Welded fabrications; Accident investigation; Repairs

1. Introduction

Companies transporting natural gas have thousands of miles of buried pipes, which date back to the 1940s and 50s. At that time, protection techniques against corrosion (e.g. protective coatings and cathodic protection) were not well developed, and the companies commonly face defects due to corrosion degradation. Worldwide, the most common way to repair gas leakage is to change the defective portion of the pipe. To do this, however, it is necessary to stop pumping gas and vent the affected portion of the line. Where there are no loops to deviate the gas flow, doing this means stopping provision of gas to some areas, with the consequent losses to the users and the transporting company. One of the alternatives available to minimize service losses and restore serviceability of corroded lines is the use of full encirclement sleeve repairs.

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Full encirclement welded sleeves are used to repair defects in underground gas pipelines (see Fig. 1). The reinforcements consist of two half sleeves welded lengthwise, which are also welded circumferentially to the pipe if there is a gas leakage or other severe defects. Standard designs are found in API RP 1107 [1]. These reinforcements are carried out habitually in areas where local loss of thickness or gas leakage are detected, generally due to corrosion. When a through-thickness defect is detected, reinforcements with an O ring and venting valve are used to prevent gas from reaching the welding operations. This kind of repair requires a circumferential (girth) fillet weld to the pipe, to prevent gas leakage during subsequent service. The possibility of repairing gas leaks is probably the most important advantage of welded sleeve repairs over competing techniques, such as clock springs [2].

In-field welding of these sleeves is normally a difficult task. Usually, short times and poor soil or weather conditions mean that cutting, handling and welding the sleeves to the buried pipes requires especially trained personnel and equipment. It is no surprise, therefore, that several weld repairs fail in different ways. These failures have in many cases been the driving force for changes and improvements in the fabrication of the sleeves, field welding procedures and non destructive testing of the repairs [3–6].

If not properly trained, due to the fear of burning through the pipe, welders tend to minimize the welding time and use high deposition rates, which are obtained with cellulosic electrodes. The use of cellulosic-coated electrodes is a common practice in the construction of pipelines but for welds made onto in-service pipelines there is a serious risk of reduction in ductility and toughness by hydrogen cracking [7]. High cooling rates as the result of the ability of the flowing gas to remove heat from the pipe wall generates accelerated cooling rates that can produce hard microstructures susceptible to hydrogen cracking. Decomposition of the cellulosic-coated electrodes is a primary source of atomic hydrogen into the molten pool. Because of that, low-hydrogen electrodes and procedures are preferable [8]. Normal basic electrodes require care during manipulation because they can pick up moisture from the air and become a source of hydrogen. Proper drying of basic electrodes can not always be guaranteed during in-field emergency repair procedures. Because of that, low-hygroscopic basic electrodes are now recommended, along with specified preheats and heat inputs to avoid high cooling rates and burn through [9].

Two incidents have been reported involving fillet welds of full encirclement sleeves. In 1985 an incident resulting in a explosion related to a previously installed sleeve was reported [10]. In 1986 a rupture occurred in an oil line following a sleeve installation [11]. The object of this work is to present the studies involved in the analysis of the causes that produced the appearance of the following defects in full encirclement sleeve reinforcements placed in a 24 in. gas pipeline: Failures 1 and 2 — cracks and fracture in a longitudinal fillet weld; Failure 3 — gas leaks in a circumferential sleeve-to-pipe fillet weld.

An extensive study of the available information was carried out, regarding technical data of the component, drawings and assembly data, welding procedures, operational conditions and records of flaws and other events. Careful circumferential and longitudinal measurements of the interferences and gaps were carried out, and samples were extracted for microstructural and fractographic analyses.

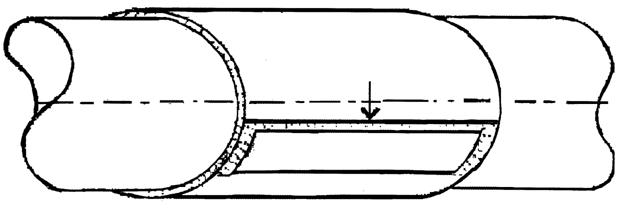

Fig. 1. Full encirclement sleeve repair of a 24 in. pipe.

Spectrometric chemical analyses were carried out, and microstructural characteristics of the materials were verified by means of optical microscopy (×10 to ×1000). Their correspondence with the corresponding specifications was verified. Mechanical tests of extracted samples from base and weld metals near the failed regions, and extensive hardness testing in all three failed specimens, and toughness and tensile testing of samples taken from the specimens were carried out, with the purpose of determining the possible effect of mechanical properties on the probability of failure. The cracked sectors on the longitudinal and circumferential welds of the reinforcement sleeves were analyzed, and samples of the defective regions were extracted.

All three failed full encirclement sleeve reinforcements were field welded, to repair gas leaks due to external corrosion in an API 5L X52, 7.14 mm thick gas pipeline. Visual and microstructural observations of the flaw areas show that all three had been welded using a 4 mm diameter cellulosic electrode. Two of them (Failures 1 and 3) present several passes that allow one to suspect that they were carried out to repair flaws in the original welds. Sleeves and side plates are also 7.14 mm thick.

2. Fractographic evaluations

Figs. 2 and 3 show in detail the surface aspects of Failures 1 and 2, respectively. Note the longitudinal side plate, and the crack in the fillet weld. In both cases the full encirclement sleeve repair shows the central portion of the longitudinal weld wide open. Both cracks were produced in the field welded joint. Fractures in both specimens initiated around the central wide open section, and propagated longitudinally toward the ends of the sleeve, in the sleeve material. Both ends of the cracks stopped close to the circumferential weld (see Fig. 4).

In the first failure, the fracture runs along the longitudinal fillet weld. In Failure 2, both extremes of the propagating crack differ in that the left side propagates in the sleeve material, while the right side propagates into the material of the longitudinal side plate. Since both parts are separated by an uncracked ligament of weld metal, as shown in Fig. 3, it is concluded that the fracture initiated in two different sites. The first fracture was probably initiated in the wide open region seen in Fig. 3. Fig. 2 shows that the failed longitudinal weld in Failure 1 has at least four weld beads, while the rest of the sleeve is welded with only one bead (see Fig. 4). This longitudinal weld was probably repaired after a flaw in the original weld was detected. Welds in Failure 2 are all single-pass, including the failed one shown in Fig. 3.

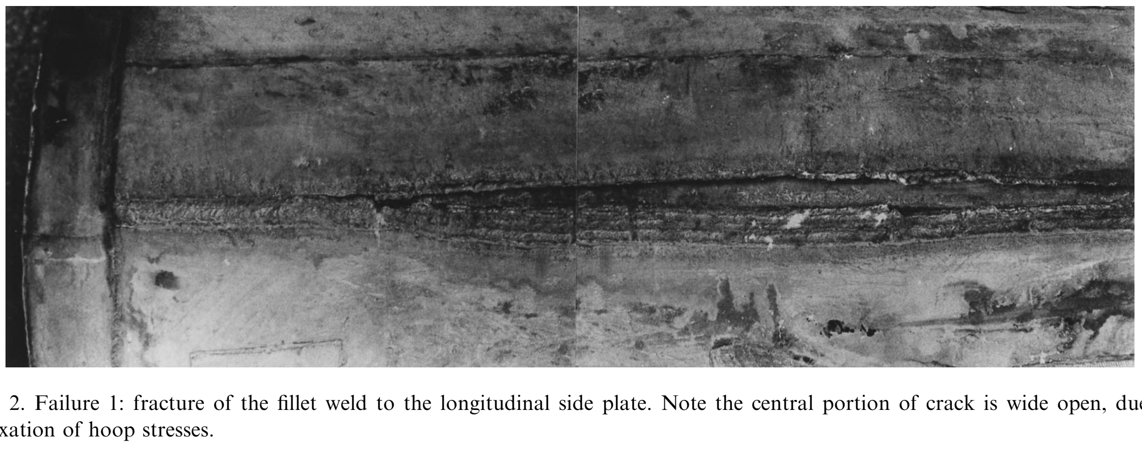

Fig. 2. Failure 1: fracture of the fillet weld to the longitudinal side plate. Note the central portion of crack is wide open, due to relaxation of hoop stresses.

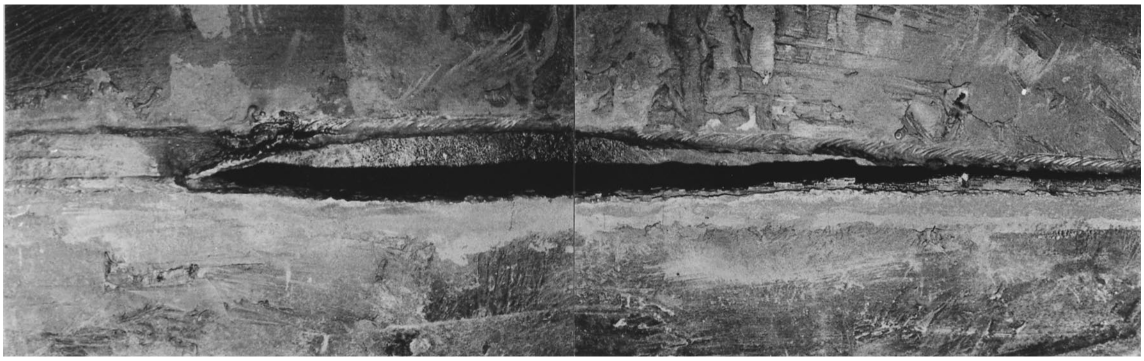

Fig. 3. Failure 2: fracture of the fillet weld to the longitudinal side plate. Note uncracked weld material to the left of the picture.

The left side part of the crack in Failure 2 has a stepped crack surface, of the type found in lamellar tearing, see Fig. 5. This same feature is seen in both failures. Cross sections of both fractures were cut, polished, and etched with Nital 5%. Fig. 5 shows the sleeve side of the fractured weld in Failure 1. Note the sleeve material at the bottom and the many weld beads on top. The crack runs between the weld and the side plate materials. Note that the crack surface is bent in order to follow the weld–base metal interface, especially evident in the area of the final bead, on top. This final bead broke several times and remained partially on both sides along the length of the fracture, giving the idea of a stepped outer crack surface, as seen in Fig. 2. Fig. 6 shows the fracture surface in the region of Fig. 5. Note the

Fig. 4. Circumferential weld of fractured full encirclement repair. Note single pass fillet welds, and longitudinal crack ending close to the circumferential weld.

inclined part at the top, corresponding to the final bead, and the brighter region near the outer surface of the sleeve, in the middle of the picture. This 3 mm thick brighter region corresponds to the weld root surface, see the weld ripples in it. It can be concluded that a gap of about 3 mm was present between sleeve and side plate at the time of welding. This gap is due to misalignments not corrected during in-field positioning.

Fig. 7 shows the fractured weld in Failure 2. Note the sleeve material to the right, side plate material to the left, and the single weld bead at center. The crack runs in the sleeve base material, that is, corresponds to the right side of Fig. 3. Figs. 6 and 7 reveal the stepped nature of the fracture in both specimens. With a closer look, it can be seen that secondary cracks start from the inner part of the serrated irregularities of the main crack surfaces, and propagate normally into the sleeve base metal.

Fig. 8 shows a top view of Failure 3. This is a crack in the circumferential sleeve to pipe fillet weld, or girth weld (see Fig. 4). The fracture runs between the weld and sleeve materials. Fig. 9 shows the weld–side fracture surface, after the fractured pieces were split open for inspection. Note the weld material, with signs of ripples as if it was cast in a mold rather than mixed with base material. It can be concluded that this fracture was due to large defects of the lack of fusion of sleeve base metal during welding. Fig. 10 shows a polished and etched cross section of a piece close to the region shown in Fig. 9, before splitting the fractured sides. Fig. 10 shows that the failed girth weld in Failure 3 has at least five weld beads, while the rest of the sleeve was welded with only one bead. Again, this girth weld was probably repaired after a flaw in the original weld was detected. Fig. 11 (×25) shows a close up of the root region of the girth weld shown in Fig. 10. Note that the crack has a singular path and is rather wide. At the right of the crack, the base metal does not show signs of having been affected by the weld

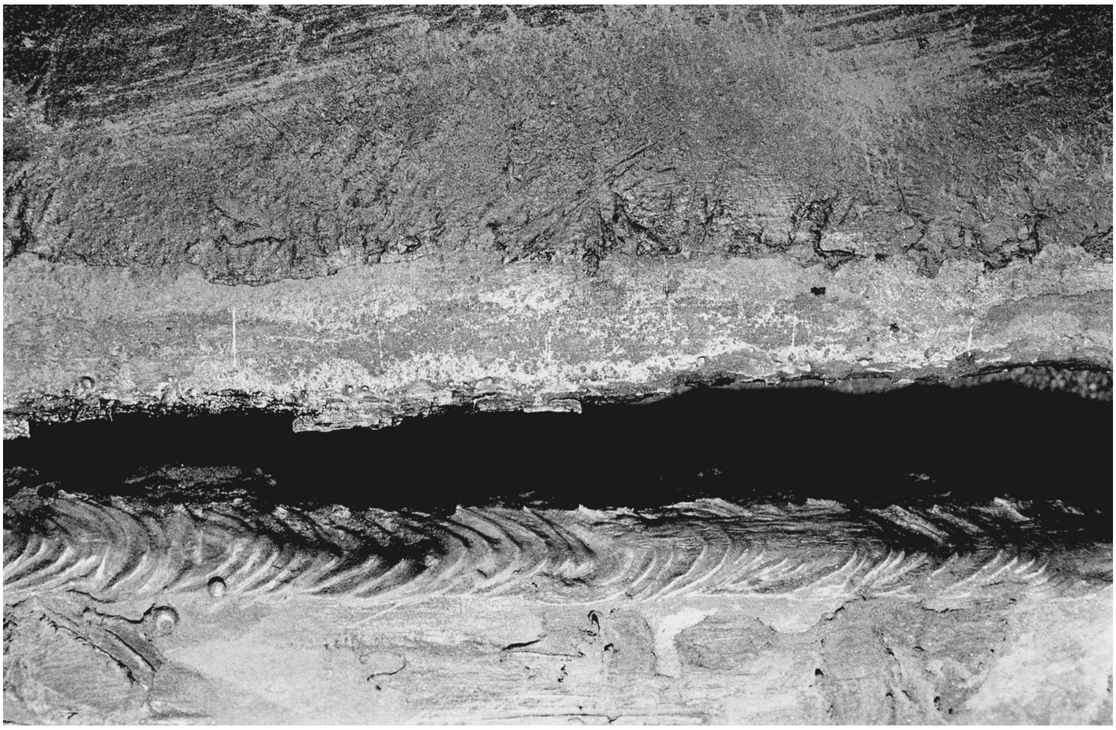

Fig. 5. Typical stepped crack surface, in HAZ of sleeve base material.

heat. Between the crack and the weld material at the left, there is a transition fine microstructure clearly differentiated.

3. Microstructural and mechanical characterization

Metallographic specimens from each of the failures were prepared for microstructural examination. Fig. 12 shows typical microstructures of base metal, weld metal and HAZ. Note the severe microstructural banding of the base metal, running parallel to the sleeve surfaces. This banding is typical of pipes, and is due to the lamination process during the fabrication of the tube from plate material. Fig. 13 (×100) shows a micrograph of the microstructure close to the fracture surface shown in Fig. 8. A large number of inclusions are present in the material, which are also aligned. Some of these inclusions are very long and shallow. Elongated type II MnS and planar arrays of oxides or complex oxy-sulphide inclusions are preferential sites for initiation of hydrogen damage. This damage has been identified as a loss of mechanical properties in pipe line steels, where hydrogen accumulates at microvoids which have previously formed at the interfaces of non-metallic inclusions [12]. Some of them are actually parallel cracks running in the rolling plane of the plate, and tend to appear coalesced in front of the secondary cracks, as shown in Fig. 7.

Table 1 shows the chemical composition of the failed sleeves. Table 2 shows the tensile properties of the three failed specimens: pipe of specimen 1, sleeve of specimen 2 and pipe of specimen 3. Properties were evaluated in longitudinal (L), circumferential (C) and through thickness (T) directions. Strength and ductility values for all materials are within the specifications of API 5L for grades ×42 to ×56.

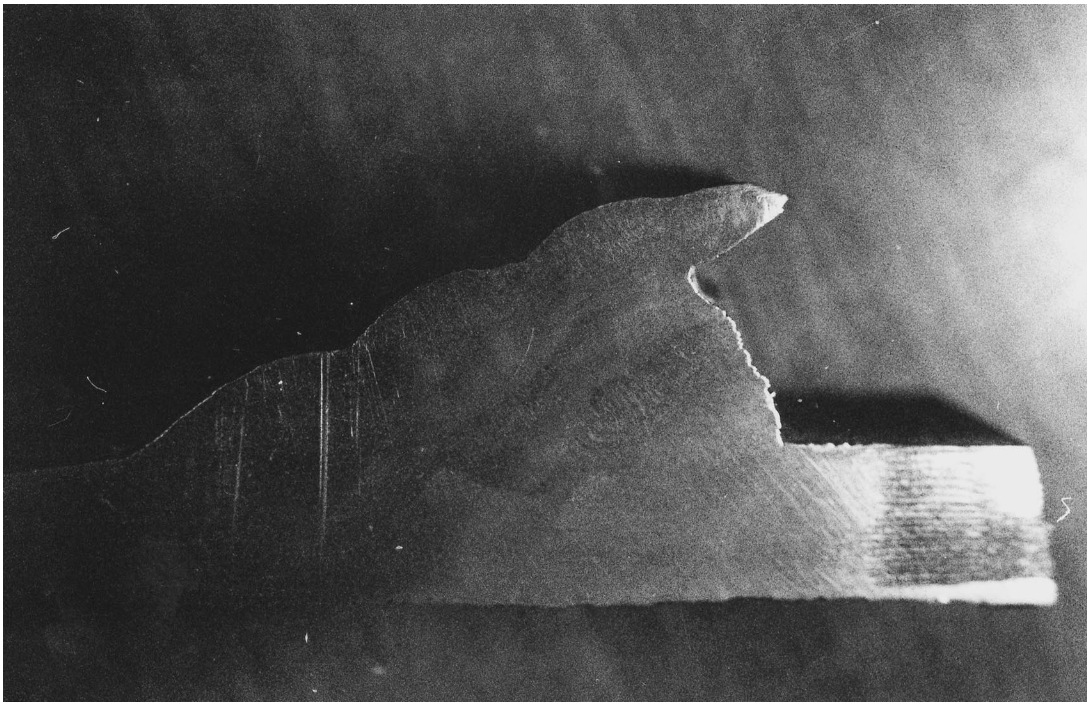

Fig. 6. Cross section of the sleeve side of fractured weld in Failure 1, polished and etched. The crack surface follows the weld–base metal interface. Note many weld passes.

Fig. 7. Cross section of fractured weld in Failure 2. Note the stepped nature of the fracture, with perpendicular secondary cracks into sleeve base material.

Note however that in the T direction all tensile properties are much lower. Ultimate tensile strength is 20% lower in the pipes, and 35% lower in the sleeve material, than strengths in the longitudinal direction. Ductility is almost zero in the T direction. The shape of the fracture surfaces on the specimens was also markedly different, fibrous in the L and C directions, and bright, fatty and banded in the T direction. This appearance is typical when the fracture runs across nonmetallic inclusions.

Table 3 shows the K_{Ic} fracture toughness properties of the failed specimens. Since small scale plasticity can not be ensured in specimens taken from a 6.5-mm thick pipe, elastic plastic J–R curves were experimentally determined for C–L pipe specimens taken from Failures 1 and 3, loaded in the circumferential direction. K_{Ic} values were then determined from the obtained J_{Ic} initiation values. Minimum K_{Ic} was 150 MPa $m^{1/2}$, which is reasonably high for a material of this kind and age.

Tensile and fracture properties shown in Tables 2 and 3 correspond to unaffected base materials. However, the fractures take place in a localized region of the HAZ, where properties are expected to be below average. Estimations of tensile properties from correlations with the micro hardness measurements on base material (BM), weld material (W) and heat affected zone (HAZ) are shown in

Table 1
Chemical composition of failed sleeves

Specimen	C (%)	Mn (%)	P (%)	S (%)	Si (%)
1	0.17	1.28	0.03	0.02	0.25
2	0.18	1.35	0.02	0.02	0.27
3	0.16	1.20	0.02	0.02	0.24

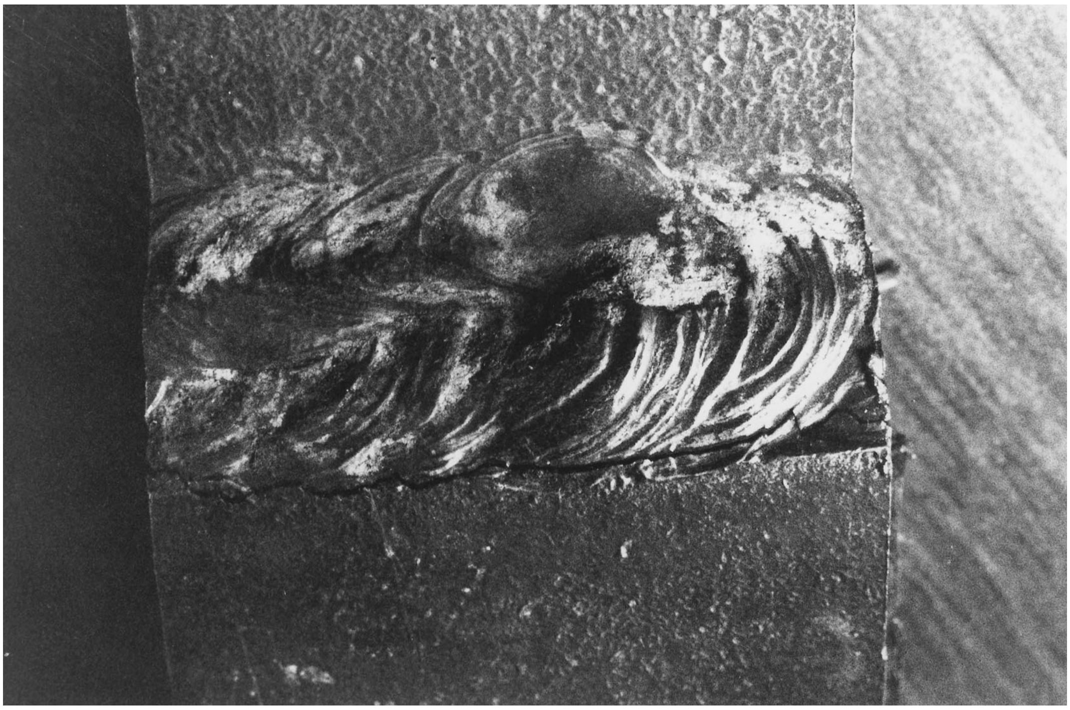

Fig. 8. Failure 3, a crack in the sleeve-to-pipe girth weld runs between the weld and sleeve materials.

Table 2
Mechanical properties of failed specimens: pipe specimen 1, sleeve specimen 2 and pipe specimen 3, in longitudinal (L), circumferential (C) and through-thickness (T) directions

Specimen	Sy (MPa)			UTS (MPa)			Elongation (%)			Area reduction (%)		
	L	C	T	L	C	T	L	C	T	L	C	T
Pipe 1	426	414	360	576	562	451	23	19	< 5	66	52	0
Sleeve 2	400	414	280	518	530	347	20	23	< 5	62	45	< 5
Pipe 3	367	412	350	500	525	446	25	19	< 5	64	52	< 5

Table 3
Fracture toughness properties of failed specimens: pipes from Failures 1 and 3, loaded in the circumferential direction

Material	Diameter (in.)	Thickness (mm)	J_{Ic} (N/mm)	K_{Ic} (MPa m$^{1/2}$)
1	24	6.5	168	165
3	24	6.5	98	150

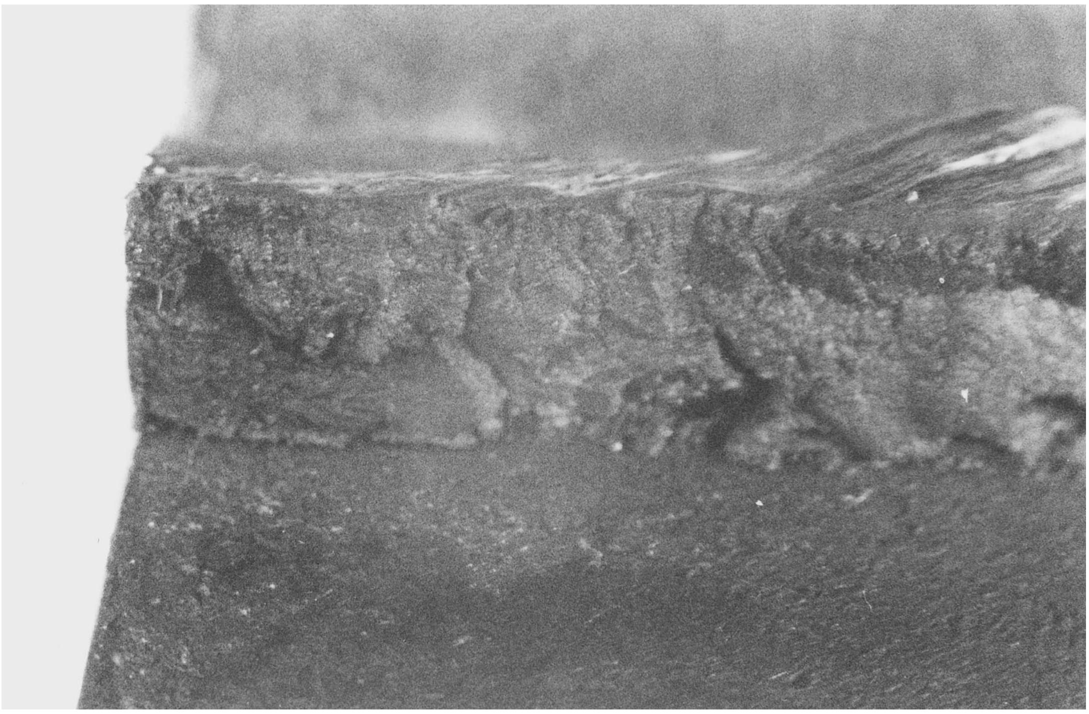

Fig. 9. Weld–side fracture surface, showing signs of lack of fusion.

Table 4. Bibliographic references [13] define a lower limit for fracture toughness of the HAZ of an API XL 52 steel. This value, of the order of 70 MPa $m^{1/2}$, is very conservative for the present analysis. At the moment of an eventual fracture the crack should extend away from the 4 mm deep HAZ, into sleeve or pipe material. Therefore, to consider a K_{Ic} similar to that of the base material, 150 MPa $m^{1/2}$, is realistic.

Crack driving forces for the propagation of the longitudinal cracks in the reinforcements are related to the hoop stresses. Relative displacements between the different parts of the cracked sleeves and the pipe were measured, before and after cutting the remaining uncracked length of each reinforcement. The relaxation of the hoop stresses, produced by the propagation of the cracks and the circumferential cutting of the sleeves, produce radial and perimetral displacements that can be related to the original stress conditions. Perimetral displacements of 30 mm and maximum diametral displacements of 10 mm were recorded after cutting the girth welds and uncracked lengths of the two cracked reinforcements investigated. These remaining stresses are not related to pressure, but rather to the contraction forces

Table 4
Average Rockwell C hardness values of circumferential joint, Failure 3, converted from Vickers micro hardness mappings and estimated UTS

Material	HV	R_C	UTS (MPa)
Base metal	186.3	> 20	598
Weld metal	225.1	> 20	680
HAZ	277.1	28	877

generated by the clamping methods during the repair procedure and the contraction of the longitudinal and circumferential welds. Since pressurization of the pipe to sleeve gap occurs through the gas leak during service, the 60 kg/cm^2 inner pressure expands the reinforcement, and therefore the hoop stresses due to inner pressure are transferred into the sleeve material.

The through-thickness stress profile was evaluated using the methodology of the R6 document [14]. Considering the stresses due to pressure and weld contraction, membrane and bending stress components of 138 and 39 MPa were defined using a simple analytical model. These stresses contribute to plastic collapse of the pipe and they are, therefore, categorized as primary stresses [15]. Maximum transverse welding residual stresses can be assumed of the order of the material yield strength, since welds were not subjected to stress relief post weld thermal treatment [16]. Residual stresses are secondary stresses that do not contribute to plastic collapse.

The failures analyzed in this study did not produce particularly severe losses, because they lead to gas leakages. Once leaks were detected, the company had time to proceed to the normal procedures in order to replace the defective portion of the pipe. A much more serious situation would be if any of the longitudinal or circumferential cracks propagated into the pipe and eventually propagated a fast fracture, generating a blowout. The longitudinal cracks studied in this work stopped a short distance from the girth weld. In that region there is a local steep reduction in the hoop stresses in the sleeve material. Firstly, the longitudinal contraction of the girth welds generates compressive residual circumferential stresses in the nearby base material. Secondly, the girth weld transfers the hoop stress due to pressure to the pipe material. However, if a longitudinal crack has a driving force large enough to reach the girth weld, the residual stresses become tensile, with which the crack driving force increases substantially and the probabilities for the crack to continue growing in the pipe material are high.

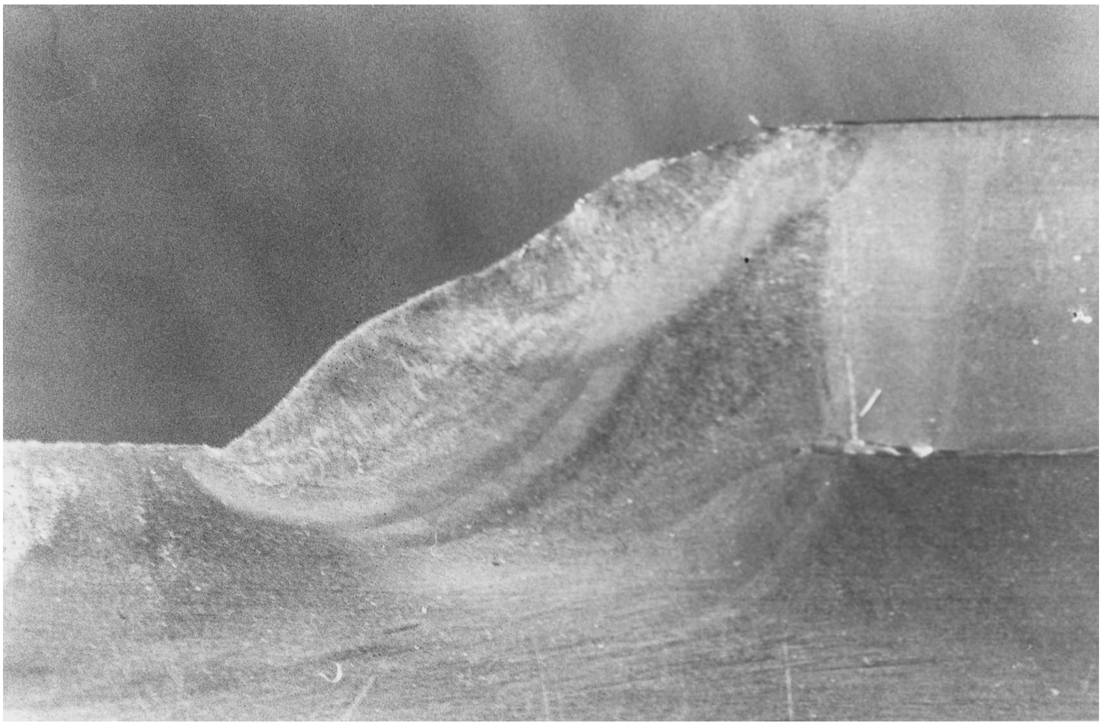

Fig. 10. Cross section of cracked region in Failure 3. Note at least five weld beads, a sign of possible repair after an original flaw.

A careful examination of pipe material in Failure 3 shows a small surface brittle crack initiating at the toe of the girth weld in the coarse-grained heat-affected zone (HAZ), as shown in Fig. 14. The maximum crack depth is 1.64 mm. The effect of banding once the crack reaches the unaffected base metal is readily apparent. The characteristics found in this crack are typical of cold cracking at the weld toe, due to the presence of a hard, susceptible HAZ (see Table 4). This hard microstructure was probably produced by high cooling rates in a moderately hardenable steel, along with high hydrogen content in weld metal derived from the cellulosic electrode and poor cleaning. High residual stresses are very likely, due to the intrinsicly high restraint of the parts during the repair weld, probably increased by a poor fit of the sleeves.

When the crack initiates in the girth weld (as in Failure 3), it could also be possible that a crack propagates into the pipe. Failure 3 showed the presence of cracks in sleeve material of a depth similar to the sleeve thickness. This defect finishes in the area of the root of the weld, on the surface of the pipe. There is a probability that this circumferential crack proceeds into the pipe material, probably favored by lamellar tearing if the pipe is an old material (which is often the case). In this case, the crack would probably not be normal to the surface of the pipe. On the other hand, circumferential cracks in the pipe material HAZ, as that shown in Fig. 14, can directly propagate through the thickness.

A hypothetical 2 mm deep and 100 mm long crack was chosen as a starting point for the calculation of the critical size of cracks in these two situations. The calculation procedure within the R6 consists of varying the size of the crack whilst maintaining the depth/length (a/c) relationship constant [14]. The critical crack size is obtained when the representative critical point falls on the curve that defines the failure assessment diagram (FAD). The ordinate axis, Kr, represents the ratio between the applied K and the fracture toughness of the material, while the abscissa Sr represents the ratio between the applied

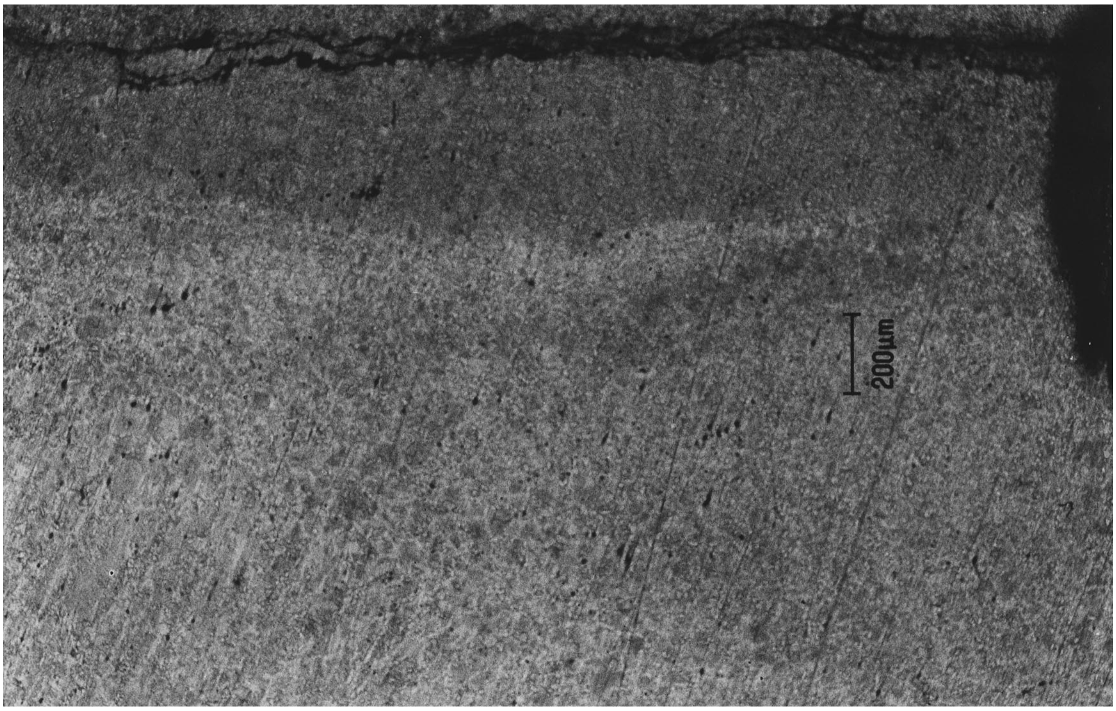

Fig. 11. × 25, root region of the cracked girth weld. At the right of the crack, base metal does not show signs of having been affected by the weld heat.

stress and the yield stress of the material. The FAD of Fig. 15 shows the range of critical crack values, assuming a conservative HAZ toughness value of 100 MPa $m^{1/2}$. The critical depth of a circumferential crack in the pipe material is 4.2 mm, that is, about 2/3 of pipe thickness. Failure is predicted as plastic collapse rather that fracture. The leak-before-break condition for this circumferential crack is amply satisfied. This, however, is of little use, since a burn through during the repair operations would lead to a very serious accident. On the other hand, the leak-before-break analysis for a hypothetical longitudinal crack that could run into the pipe material depends critically on the crack surface length [15,16].

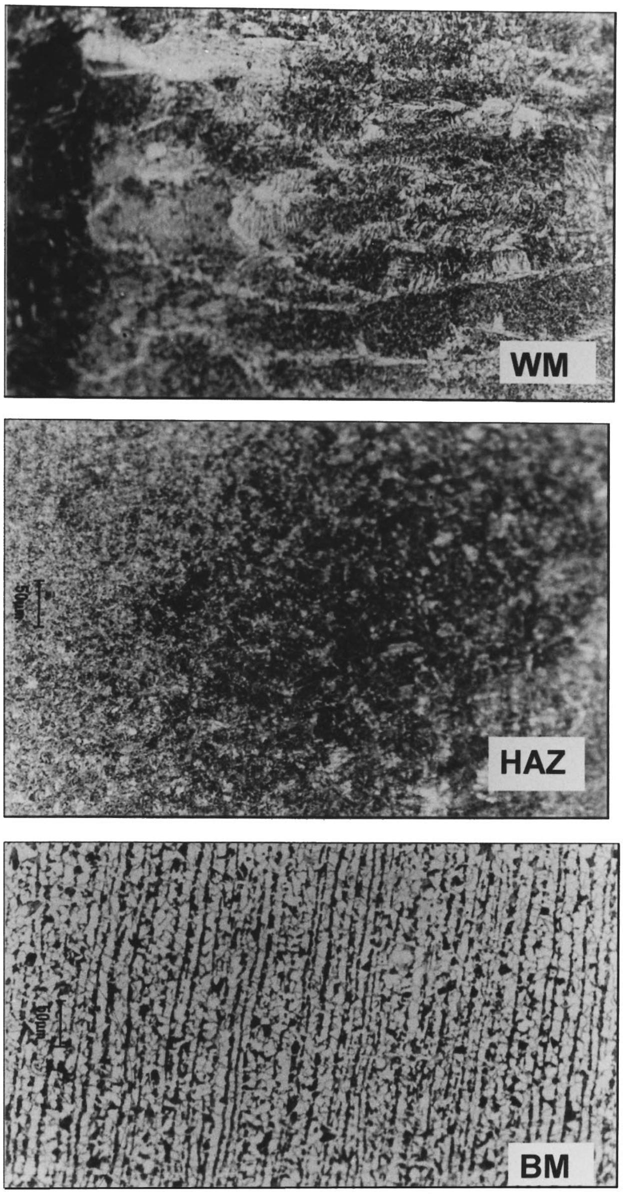

Fig. 12. Typical microstructures of basae metal (BM), weld metal (WM) and heat-affected zone (HAZ) (×2000).

Assuming a conservative HAZ toughness value, within a weld residual stress field, this leak-before-break condition may not be satisfied unless we assume that a successful post weld heat treatment is done after the repair, which is not normally done in field conditions.

4. Discussion of results

4.1. Failures 1 and 2: poor base and weld metal quality

Old steels used to have a large amount of inclusions, but that has diminished as the steel making industry developed better production procedures. During laminating of the pipe, these inclusions tend to form bands, which are parallel to the pipe surfaces. This banding creates planes of very low through-thickness (or transverse) mechanical properties. Hydrogen pick-up during welding processes with cellulosic electrodes can also contribute to the loss of mechanical properties in the transverse direction because it can accumulate at previously formed microvoids at the interfaces of non-metallic inclusions, and propagate cracks from pressure accumulation of molecular hydrogen. Experimental testing shows that the strength in the transverse direction is about 1/2 to 2/3 of the longitudinal strength. In the original conditions this low transverse strength did not affect the strength of the pipe to a large extent, because all stresses acted in the longitudinal or circumferential directions. This is assured because pipes were all butt welded. When sleeve repairs are made, however, fillet welds are used for both the sleeve-to-side plate longitudinal welds and the sleeve-to-pipe circumferential welds. Fillet welds are well known for transferring the load via shear loads, which generate important tensile stresses in the transverse

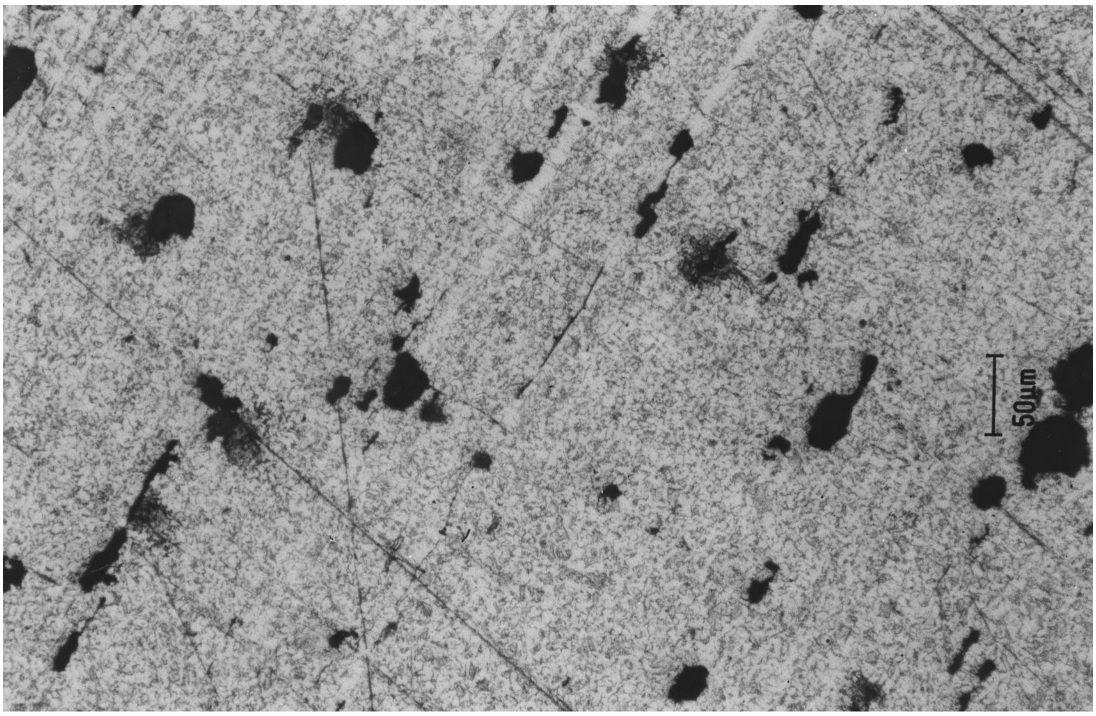

Fig. 13. × 100 micrograph of the microstructure close to the fracture surface of Fig. 8. Note microstructural banding, aligned inclusions, and parallel microcracks.

(through-thickness) direction. The low resistance of the material to transverse loads makes it prone to lamellar tearing.

Other factors involved in the occurrence of the failures can be found in the procedures used when assembling and welding the field joints. A high hydrogen, cellulosic electrode was apparently used to weld the field joints, and therefore hydrogen damage and other defects were probably introduced into weld metal and HAZ. Weld beads are large, indicating that high welding amperage and waving techniques were used. These conditions further increased the tendency to HAZ brittleness. Finally, relatively high circumferential stresses were introduced into the sleeve assembly, due to the use of hydraulic compressing systems and clamps to fit the sleeves onto the pipe surface and reduce gaps. Note that two 30 ton rams are used in the process, and that it is common to see that 5 mm gaps are eliminated in this way.

4.2. Failure 3: gas leaks in circumferential weld

Penetrant ink testing of the circumferential welds allowed us to detect flaws in the junction of the weld and the sleeve metal. This circumferential weld has at least three weld beads, while the rest of the sleeve is welded with only one bead. This circumferential weld was probably repaired after a flaw in the original weld was detected. A 30 cm long, 10 cm wide window was flame cut to take apart the flawed region of the circumferential weld. Then, samples were machined off. During saw cutting, one part of the welded joint opened up in two. A fractographic study of the flaw surfaces show that two regions can be identified: in some zones, the weld ripples indicate that the weld metal did not melt the base metal, while in other zones some evidence of fracture is apparent.

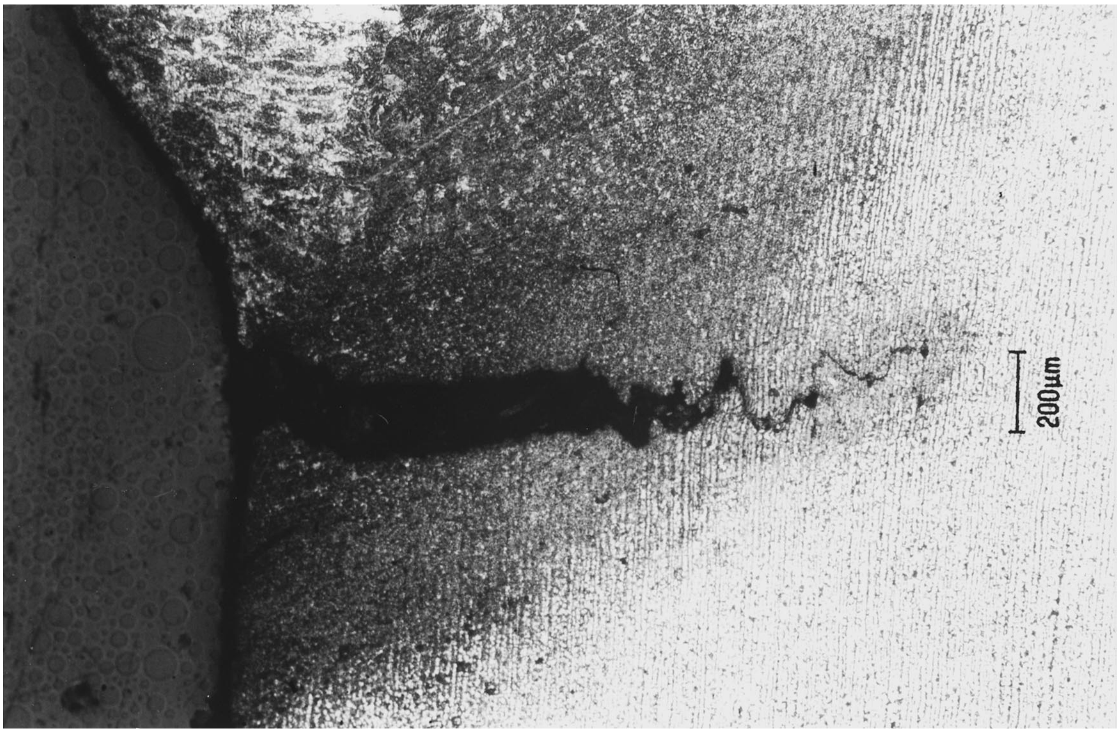

Fig. 14. Toe crack in pipe material HAZ of girth weld in Failure 3 (×50).

Microstructural examination of cross sections of the samples shows a wavy interface between weld and base metals, along the whole thickness of the sleeve. At the interface in the region of the root pass, two different microstructures corresponding to the two unmixed materials are evident. Severe lack of fusion on the sleeve side of the circumferential weld was the main reason for the failure of the original weld. Further attempts to repair it were not successful. Although the propagation modes of the flaw into the repair weld were not detected, attempting to repair a weld with lack of fusion by simply adding more weld metal could by no means be successful.

4.3. New procedures for repair welds

In order to minimize the recurrence of these types of failure, the following recommendations were made:

- to improve the in-plant fabrication of the half sleeves to be used in the repairs, by using good quality new pipe material, and reducing geometric errors;
- to improve the in-field installation of the repair sleeves onto the pipeline, by using qualified welding procedures, improving weld procedures (low current, multiple pass — straight bead welds, 45° electrode inclination, etc.), reducing pipe-to-sleeve gaps down to a maximum of 3 mm, and using low hydrogen electrodes.

New quality procedure specifications for the in-plant fabrication of the sleeves to be used in the repairs

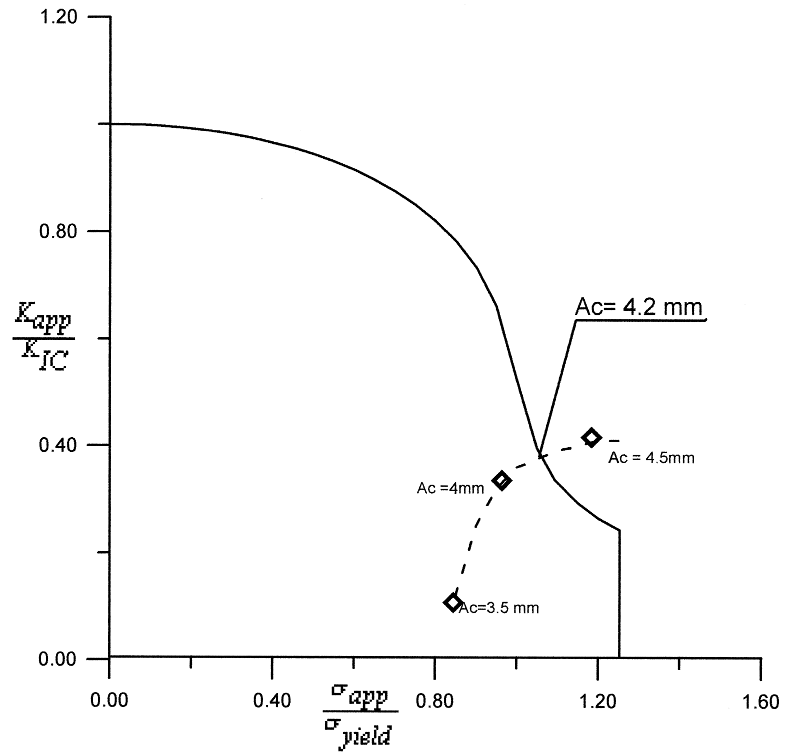

Fig. 15. Failure assessment diagram of circumferential cracks in pipe HAZ of girth weld.

were implemented, in order to avoid poor fit in the field which lead to poor quality side seams. A new low hydrogen procedure for welding onto in-service sleeves was developed and verified in the field. The new procedure includes the use of small diameter low hygroscopicity basic coated electrodes (type E7018) with a specified maximum heat input of 1.6 KJ/mm, maximum and minimum speed and 45° electrode inclination. For the experimental qualification of the procedure according to API 1104 and 1107, API 5L X52 tubes were welded in a specially built loop with gas flow. This procedure was verified experimentally in the field to produce penetrations of about 1.5 mm. A quality procedure for pre-repair and post-repair operations was also developed. This procedure includes thickness measurements to verify the minimum weldable wall of the pipe thickness, in order to avoid the occurrence of tube perforation during the circumferential reinforcement-to-pipe weld, and magnetic particle or dye penetrant NDE.

Experimental measurements of stress states in the sleeve repairs were carried out in the loop. Between 6 and 8 strain gauges were placed in each test, in both circumferential and longitudinal directions. Work was done to verify the effects on the stress fields of the following variables: the amount of pressure reduction during welding, the load and place of positioning clamps, the length of the repair sleeves, the use of O ring-based devices to prevent gas leakage from reaching the welds, dynamic loading on the sleeves after breakage of the O ring following closure of the venting valve, and the influence of a middle circumferential weld on double (tandem) sleeve repairs [17]. These results compare well with those reported by Gordon et al [18], in which they present details of a 3-year project to develop fitness-for-purpose assessment procedures for sleeve and branch welds in pipelines [18]. They analyze the influence of different geometric variables involved in full encirclement (circumferential) welds, and develop a procedure to determine their fitness for service. Full-scale fracture tests were performed to validate the assessment procedures developed, and residual stress measurements were obtained on a welded sleeve assembly using the neutron diffraction method.

The use of an epoxy hardenable interstitial filler was also incorporated into the repair procedure, to minimize the gap between the full encirclement sleeve and the pipe. In this way the possibility of plastic collapse can be reduced. Local collapse of the pipe wall under full encirclement sleeve reinforcements is associated with breaks and blowouts that cause large gas losses and abrupt depression in gas pipelines. Although these defects do not represent an imminent risk of failure, they should be eliminated because they impede the normal passage of the smart pig for internal inspection. The effects of different geometric factors were numerically assessed via non linear finite element modeling of fluid flow and pipe response. All possible causes of the appearance of these defects and measures to minimize their occurrence were evaluated. Two procedures for applying epoxy fillers were developed, to be used in normal full encirclement sleeve repairs and in repairing gas leaks [19].

5. Conclusions

Based on the metallurgical and mechanical analyses, the cause of the failures of three full encirclement sleeves has been related to poor manufacturing standards. The main reasons of the failures are:

- the material used to build the sleeves was old and had poor transverse strength;
- a high heat input, single pass weld procedure using a high hydrogen, cellulosic electrode was used to weld the field joints;
- loss of mechanical properties caused by hydrogen and other defects affected both weld metal and HAZ;
- relatively high circumferential stresses were introduced into the sleeve assembly;
- lack of fusion, and other weld defects were introduced by poor weld standards.

In order to minimize the recurrence of these types of failure, a series of changes were introduced, including improvements in the in-plant fabrication of the sleeves and the in-field installation of the repair sleeves into the pipeline, and the use of a new low hydrogen weld procedure with controlled penetration. NDE specifications now include thickness measurements to verify the minimum weldable wall of the pipe (in order to avoid tube perforation) plus magnetic particle and dye penetrant crack detection. Additionally, the use of epoxy hardenable interstitial fillers was introduced to minimize the risk of sleeve failures and plastic collapse of the pipe.

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References

[1] American Petroleum Institute. Recommended pipeline maintenance welding practices. API RP 1107, USA.
[2] Kiefner JF. Defect repair procedures. In: Proceedings of the Sixth Symposium of Pipeline Research. Houston, USA, 1979. p. I.
[3] Report GIE 2-11/97. Failure analysis of field welds of full encirclement sleeve repairs. Transportadora de Gas del Norte S.A., Argentina.
[4] Chapetti MD, Otegui JL, Manfredi C, Martins CF. Full scale experimental analysis of stress states in sleeve repairs of gas pipelines. Int'l Journal of Pressure Vessels and Piping 1999 (submitted).
[5] Trunzo A, Otegui JL, Manfredi C, Martins C. Capacitación de personal para soldaduras de reparacion en gasoductos. In: Proceedings of the VI Latinamerican Welding Conference, Buenos Aires, 1999.
[6] Report GIE 2-11/97: Análisis De Falla De Soldaduras De Campo en Tres Refuerzos De Unión Recta. Transportadora de Gas del Norte S.A., Argentina, 1997.
[7] Welding handbook. 3rd ed., vol. 1. American Welding Society, 1989.
[8] Bruce WA, Threadgill PL. Effect of procedure qualification variables for welding onto in-service pipelines. AGA, Project No J7141, July 1994.
[9] Report GIE 3-11/97: Field welding of full encirclement sleeves. Procedure qualification and training of personnel. Transportadora de Gas del Norte S.A., Argentina, 1997.
[10] National Energy Board. "In the matter of an cccident on 19 February 1985 near Camrose, Alberta, on the pipeline system of interprovincial pipe line limited". National Energy Board Report, MH-2-85, June 1986.
[11] Kniefner JF, Bruce WA, Stephens DR. Pipeline repair manual, AGA Cat. No L51716, 1994.
[12] Biefer GJ. Materials Performance 1982;21(6):19.
[13] Eiber RJ, Kiefner JF. Pipeline failures, ASM International, 1996.
[14] Nuclear Electric. R6-CODE: software for assessing the integrity of structures containing defects. London, UK, 1993.
[15] BSI PD6493/91 "Guidance on some methods for assessing the acceptability of flaws in fusion welded structures". British Standards Institution, London, 1991.
[16] Challenger NV, Phaal R, Garwood SJ. Fracture mechanics assessment of industrial pressure vessel failures. Int J Pres Ves and Piping 1995;61:433–56.
[17] Anderson TL. Fracture mechanics, fundamentals and applications. 2nd ed. Boca Raton, USA: CRC Press, 1995.
[18] Gordon JR, Dong P, Wang YY, Jutla T. Fitness-for-purpose assessment procedures for sleeve in pipelines: Summary Report. EWI project Nos J7185, J7193 & J7215 to the American Gas Association, December 1994.
[19] Otegui JL, Urquiza S, Rivas A, Trunzo A. Local collapse of gas pipes under sleeve repairs, Int'l Journal of Pressure Vessels and Piping 1999 (submitted).