JMEPEG (1999) 8:579-590 ©ASM International

Performance of Repair Welds on Aged Cr-Mo Piping Girth Welds

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(*Submitted 2 November 1998; in revised form 4 May 1999*)

This article documents the results of an industry survey of weld repair practices and describes the results of experimental evaluations performed on service-aged 2¼ Cr-1Mo steel piping using SMAW with both conventional postweld heat treatments and temper bead repair techniques. The overall results of this program provide substantial evidence that service-aged piping systems can be successfully weld repaired with and without postweld heat treatments and that life extension by several decades is achievable under the right design and repair conditions. Weld repairs performed on degraded exservice welds resulted in restoration or improvement of tensile and creep properties. Microhardness test results within the heat-affected zone of each weldment indicated that the temper bead weld repairs produced only slightly higher peak hardness values than those measured for the fully postweld heat treated repairs. Finally, in terms of toughness, temper bead weld repairs consistently produced higher impact properties than those measured for the postweld heat treated weldments. Gas tungsten arc weld repairs with postweld heat treatment resulted in the best combination of tensile strength, uniform microhardness distribution across the weld, Charpy toughness, and creep rupture life.

Keywords Cr-Mo steels, gas tungsten arc welds, mechanical properties, postweld heat treatment, shielded metal arc welds, welding

1. Introduction

Despite the widespread use of weld repair in power plants, several basic issues remain to be addressed. The efficacy of weld repairs in terms of extending the component life has not been sufficiently quantified, because follow-up documentation of the postweld repair performance of the component is often inadequate. It is not uncommon for cracking to occur repeatedly at the same location as that of the original weld repair, eventually rendering component replacement more economical than performing a repair. If suitable life assessment techniques are available to a utility to determine how much life it is buying by weld repair, the utility can more intelligently evaluate the cost effectiveness, reliability, and life extension achieved. Frequently, several alternative repair techniques are available for a given application, and the relative advantages of any one technique over the others in terms of cost, reliability, and life extension are unclear. In performing weld repair, the overall in-service aging and the associated degradation (softening, embrittlement, substructure damage) are often not taken into account, resulting in premature cracking at other locations in the component following the weld repair. The effect of prior degradation on the remaining life of weld-repaired components needs to be quantified. Elimination of postweld heat treatments can often lead to significant reduction of repair cycle time. At present there is no industry guideline for weld repair of service-exposed components. Until recently, all weld repairs performed on 1¼Cr-½Mo and 2¼Cr-1Mo steels required subsequent postweld heat treatment (PWHT) to reduce residual stresses created by the joining process.

In 1994, the National Board Inspection Code (NBIC) reconsidered the requirement and determined that "postweld heat treatment in accordance with the original code of construction may be inadvisable or impractical" for certain repair circumstances and that alternative repair methods can be used. The revision currently places the responsibility on the operator/user to demonstrate minimum materials properties equal to those of the material used for the original construction. To address all the above issues, EPRI employed a multifaceted approach. First, a repair guideline document was prepared based on the current state of the art. Second, a detailed survey was conducted to document industry experience and practices with respect to weld repair. Last, a major experimental program was conducted on repair welds to aged CrMo piping. Extensive results from these activities have been recorded in Ref 1. This article provides an overview of the highlights of the study.

2. Survey of Utility Weld Repair Practices

A survey questionnaire was prepared and sent to approximately 60 utilities in the United States. Twenty-eight utilities responded to the survey. Responses were collated and summarized. Where percentages are given, they represent the percentage of the survey group that responded in a similar manner unless otherwise noted. Respondents included those with only a single generating unit to those with up to 41 units. Generating units range in size from 18 to 1120 MWe.

The majority of utilities surveyed indicated that all welding procedure and welder qualifications were conducted in accordance with ASME Section IX. Detailed results from the survey

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can be found elsewhere (Ref 1), and major highlights of the survey are described herein.

Repairs performed to date have concentrated on the following components: main steam headers (>200), hot reheat piping (>20), hanger/lug attachments (>200), and radiography plugs (>100). Most repairs involve girth welds (>90%) as opposed to long seams (<10%). Over one-half of the utilities reported cracking in the coarse grained heat-affected zone (HAZ) region of circumferential welds while some cracking was axial or, to a lesser extent, located in the fine grain soft zone. Only 15% of the utilities indicated observing all of the mentioned types of cracking.

Most repairs are conducted during scheduled outages. Steam piping and header repairs are normally performed by either in-house staff or a repair vendor, according to two-thirds of the utilities. Only 25% indicated that both groups were used for repairs. Outage durations vary widely and ranged from several days to ten weeks or longer. Outage costs also vary and ranged from as low as $20,000 to over $5 million on a generic basis. Nearly half of the surveyed utilities stated that all their repairs had been done in situ, or it was their preference to do so. A combination of equipment, personnel availability, and transportation considerations were cited as major factors affecting this decision.

The level of damage (e.g., creep cavitation, embrittlement, crack depth) where a component was considered nonrepairable varied. Over 30% set some level of metallurgical damage for decision purposes. Creep damage ranging from level 1 to 4 was listed by various utilities as their repair/replacement decision point. Nearly 30% of the utilities cited cost or economics rather than metallurgical or technical considerations for the determination.

Wrought and forged piping/components of 2¼ Cr-1 Mo and 1¼ Cr-½ Mo alloys are routinely repaired. Several utilities indicated working with 316H or 316N materials. Other materials listed included isolated experience with A106, C-Mo, 1Cr-½ Mo, ½Cr-½ Mo, 304N, 347, and A217 WCB/WC6/WC9. Twenty-one percent of the utilities indicated that they were considering using P91 material in hot reheat, main steam, or header piping for applications above 538 °C (1000 °F).

Nearly one-half of the utilities surveyed use some form of in-house life assessment program or methodology on high energy piping systems.

Almost 90% of the utilities surveyed keep records on the performance of their repairs. Over 60% of the utilities recorded that no further cracking had been observed. While half of those reporting cracking observed recracking within one year, the remaining half did not report recracking for two to ten years.

Only 20% of the respondents employ some form of weldability test to determine the weldability of a material for repair. Questions pertaining to what criteria and mechanical tests must be met before a component is deemed repairable also resulted in varied responses. Over 25% of those surveyed had no response. Evaluation on a case-by-case basis and analysis via nondestructive evaluation (NDE) and calculation to determine suitability to operate safely were listed most often. Where listed, mechanical testing was typically limited to tensile testing. Metallurgical tests including replication and hardness were cited in lieu of mechanical tests. Routine tests performed in support of repair welds in piping and headers revealed varying results. Over one-third of the utilities surveyed utilize replication techniques for assessing the status of the repair area. Nondestructive evaluation was listed as the second most used test and was specified by less than 20% of the respondents. Mechanical testing resulting from welding procedure qualifications was also mentioned.

Nearly 80% of the utilities reported that grinding, machining, or gouging were used for defect removal. Almost all of the utilities used either grinding or machining for defect removal. One utility cited a relatively new technique, plasma gouging, for defect removal while another utility listed a very old technique—sawing.

The shielded metal arc welding (SMAW) process was most commonly utilized by all the utilities for steam piping and header weld repairs. Only about one-half of the utilities indicated using gas tungsten arc welding (GTAW), and only one or two use gas metal arc (GMAW) or flux cored arc (FCAW) welding. Only 30% of the surveys indicated use of automatic or machine welding.

As with casing repairs, welding filler metals used for repair of specific alloys typically followed mechanical properties of the base metal. For example, 80 series filler metals were used for repair of 1¼ Cr alloys, 90 series materials were used with 2¼ alloys, and 12Cr alloys were repaired with similar chemistry weld filler metal. Others included INCO A and ENiCrMo-2 and ENiCrMo-3 for dissimilar weld metal repair.

Typical preheat temperatures, interpass temperatures, and postweld heat treatment (PWHT) temperatures were 121 to 316 °C (250 to 600 °F), 260 to 371 °C (500 to 700 °F) (maximum) and 621 to 760 °C (1150 to 1400 °F) for 1¼ Cr-½ Mo steel. For 2¼ Cr-1Mo steel, the preheat temperatures were 149 to 316 °C (300 to 600 °F), with the others being the same as for 1¼Cr-½Mo steel. All of those utilities responding indicated that heat treatment was performed locally and that the time for PWHT followed typical code criteria of 1 h/in. of thickness.

Preweld and postweld inspection was conducted using a variety of methods, with most respondents using at least visual examination, VT. The next most used method was liquid penetrant (PT), followed by dry magnetic particle (MT), fluorescent magnetic particle (FMT), and ultrasonic test (UT) methods. Factors affecting inspection include the original condition of the component, acceptable indications including porosity, voids, slag inclusions, grain size, accessibility, and poor surface finish. Radiography was used by only slightly over one-third of the utilities—an unusual response since radiography is typically required by pressure piping codes for high-energy high-pressure systems.

3. Test Program Details

The overall scope of the test program on 2 ¼ Cr-1 Mo steel piping/header material undertaken in this study is shown in Fig. 1. Girth welds removed from header/pipe sections that had been exposed in service to two different levels of degradation were chosen for the study. The initial metallographic and mechanical characteristics were established in the base metal and in the weld HAZ locations. Repairs were then performed to these girth welds using different weld repair procedures, and the metallographic characteristics and the mechanical properties of the repaired weldments were then evaluated using an extensive battery of tests shown in Table 1.

As shown in Fig. 1, five service-removed girth weldments are discussed in this report, along with five weld repairs performed to these weldments. Two specific levels of degradation were selected to represent repairs performed on component materials at different stages in service life. These girth weldments include two pipe weldments, TC6 and TC7, which represent level 1 degradation, and three header girth weldments, TC8, TC9, and TC10, which represent level 2 degradation.

The three conditions examined for each of the weldments included the following:

- Exservice base metal (designated with a BM suffix, i.e., TC6BM)
- Exservice weldment (designated with an SR suffix, i.e., TC6SR)
- Weld-repaired condition of the exservice weldment (designated with a WR suffix, i.e., TC6WR)

3.1 *Material History*

The degradation level 1 material consisted of two girth welds removed from Entergy-Gulf States Utility's Lewis Creek Unit 2 hot reheat piping system. The piping had been fabricated from a 24 in. diameter, 1.143 in. thick (nominal) ASME SA-155 Class 1, $2\,\frac{1}{4}$ Cr-1Mo material. The unit from which the piping was removed had operated for a reported 161,000 h at 538 °C (1000 °F) and had been in commercial operation since May 1971. The piping had been removed from service in the fall of 1992. Operating pressure was reported to fluctuate considerably with load with a normal operating pressure of 2.31 MPa (330 psig) and a maximum pressure of approximately 3.34 MPa (475 psig). The operating hoop stresses based on the average pressure and maximum pressure were approximately 23.8 and 33.6 MPa (3.4 and 4.8 ksi), respectively. The unit was reported to have been subjected to 138 total starts, including 82 hot starts.

The degradation level 2 material selected for the repair program was a header girth weldment removed from Ohio Edison's W.H. Sammis Plant. The header was reported to have been placed in service in 1959 and had been exposed to a total of 244,000 h of service operation. Operating temperature and pressure were reported to have been 565 °C (1050 °F) and 16.8 MPa (2400 psig). The operating hoop stresses based on the average and maximum pressures were 35 and 38.5 MPa (5.0 and 5.5 ksi), respectively. A total of 901 starts had been documented, although no differentiation between the number of hot and cold starts was available. The header had been fabricated from a 25.4 cm (10 in.) inside diameter (ID), 8.57 cm ($3\frac{3}{8}$ in.) wall, seamless pipe. It included two pipe-to-pipe girth weldments and two T girth weldments. The weldments selected for this program include the two pipe-to-pipe girth weldments (TC9 and TC10) along with one T weldment (TC8).

3.2 *Pre-repair Evaluations*

Through-wall plug samples were extracted from the various girth welds to evaluate the condition prior to weld repair. All the welds were single V welds with the backing rings still intact.

In the case of degradation level 1 piping welds (TC6 and TC7), the welds had been fabricated by SMAW followed by subcritical PWHT. The structure of the base metal consisted of tempered bainite and ferrite with an ASTM grain size of 6 to 7. The weld metal microstructure again consisted of bainite-ferrite mixtures in the midwall-to-outer diameter (OD) region and of 100% bainite in the midwall-to-inner diameter (ID) region. The coarse grained heat-affected zone (CGHAZ) consisted of 100% tempered bainite with a prior austenite grain size of ASTM 2 to 3, while the fine grained heat-affected zone (FGHAZ) showed a grain size of ASTM 10. No evidence of creep cavitation damage was found in the base metal, weld metal, fusion line, CGHAZ, or FGHAZ.

In the case of degradation level 2 header welds, the welds had been fabricated by submerged arc welding (SAW) fol-

Table 1 Mechanical tests conducted on piping/header samples

Test	Location on specimen
Chemical analysis	Base metal
Preliminary nondestructive evaluation	…
Metallographic characterization of damaged area	Composite
Microhardness/hardness traverse	Composite
Creep-rupture (566, 593, 621 °C)	Composite (cross-weld)
Large diameter creep-rupture (565 °C)	Composite (cross-weld)
Isostress rupture at 55 MPa (621, 650, 663, 677 °C)	Composite (cross-weld)
Tensile (24, 566 °C)	Composite (cross-weld)
Charpy impact	Notch at base metal and HAZ
Creep crack growth	Precrack at HAZ

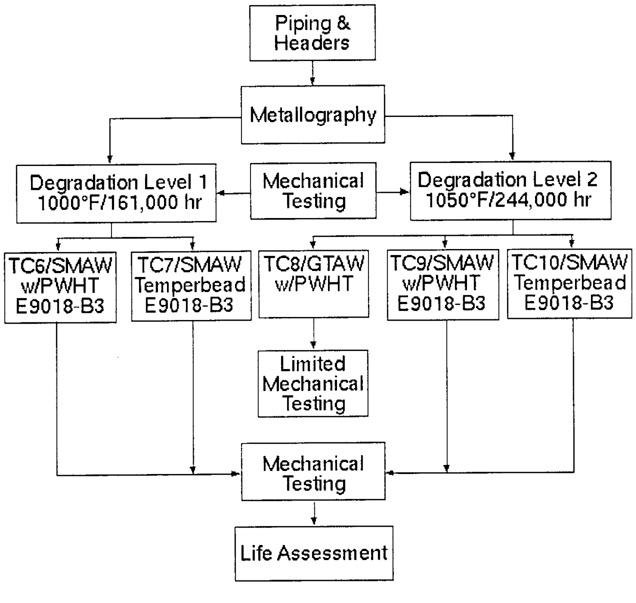


Fig. 1 Flow chart outlining the scope of the weld repair evaluations on aged $2\frac{1}{4}$Cr-1Mo steel

lowed by subcritical PWHT. Analysis of the HAZ microstructure led to the conclusion that no creep damage was evident on either side of the weldments. The FGHAZ microstructure was determined to be 100% tempered bainite with a fine grain size of ASTM 10. Analysis of the base metal determined a structure of tempered bainite and ferrite with an ASTM grain size of 3 to 4. The grain size and the carbide morphology are typical of that observed for a normalized and tempered PWHT service-exposed component.

It was the original intent of the project to utilize degraded material of varying degrees of creep cavitation. This was abandoned due to three reasons. First, exservice material with cavitation could not be obtained despite a diligent search. Second, many experts consulted felt that creep cavitation normally occurs in this steel after considerable life exhaustion (>80%) and that repair of such material might not be desirable. Third, it seemed that the common weld repair practice would involve excavation of all cavitated material. For these reasons, material deemed to be in the microstructurally degraded condition based on service-exposure history was considered acceptable, despite the absence of creep cavitation.

The chemical compositions of base metal and weld metal met the applicable ASME/AWS standards for the degradation level 1 piping material. The oxygen content of 440 ppm was considered typical for SMAW welds and indicated an electrode coating basic in nature. For the degradation level 2 header steel, the SAW was of the 3Cr type, and oxygen content of 1200 ppm suggested use of an acidic steel.

Ultrasonic examination indicated the presence of minor slag inclusions in the weld, as confirmed by subsequent metallography. No flaws were found at other locations.

3.3 Repair Welding

Shielded metal arc welding repair of the four service-removed girth weldments described above included two postweld heated repairs, TC6WR and TC9WR, as well as two temper bead repairs, TC7WR and TC10WR. All welding was performed employing the SMAW process following excavation of approximately one-half the diameter of the service-removed girth weldment from the piping/header. In addition, a GTAW repair, TC8WR was also performed to a degradation level 2 weld. The repair was postweld heat treated following welding. The SMAW-PWHT, SMAW-temper bead, and GTAW-PWHT repair procedures are discussed in detail in this article.

SMAW-PWHT Repair. The welding procedures for weld repairs TC6WR and TC9WR consisted of SMAW followed by postweld heat treatment. An E9018-B3 SMAW filler wire was utilized for the repair. The repair was accomplished by first excavating a cavity which extended approximately 1 cm (0.4 in.) on either side of the existing weldment toe and approximately 180° circumferentially. Arc gouging and subsequent grinding were employed for the excavation. The side wall taper was ground to 3 to 5°, and approximately 4.76 mm ($^3\!/_{16}$ in.) from the ID surface was left around the root region of the weldment. A total groove width of 5.84 (2.3 in.) at the OD was measured.

Following excavation of the cavity, the repair was performed by preheating the coupon to 232 °C (450 °F) and then buttering the sidewalls and the root region with three layers of weld metal. A 2.38 mm ($^3\!/_{32}$ in.) filler rod was utilized to butter the cavity along with a 50% overlap. The welders were permitted to utilize 3.175 mm ($^1\!/_8$ in.) or 3.97 mm ($^5\!/_{32}$ in.) rods to complete the repair. Double-up welding was employed throughout.

Following welding, the preheat was maintained for a minimum of 8 h, and then the repair was allowed to cool. This deviation from the code was considered necessary to obtain the service-removed half of the coupon for testing without exposing that half to PWHT. The weldment was sectioned into two halves (a service-removed half and a weld-repaired half). Next, the weld-repaired half was placed in a furnace, heated at 56 °C (100 °F) per h, postweld heat treated at 704 °C (1300 °F) for $1\frac{1}{2}$ h, and allowed to cool to room temperature. The repair was also x-rayed to ensure integrity. Both the repair and the service-removed weldment coupon halves were then sectioned for mechanical and metallurgical testing.

The procedures for weld repairs TC6WR and TC9WR were essentially similar to each other with minor differences in amperage and weld metal deposition rates due to differences in component wall thickness.

SMAW-Temper Bead Repairs. Weldment TC7WR was welded in an almost identical fashion to weldment TC6WR except that the weldment did not include a postweld heat treatment. Tempering from the buttering (temper bead) was employed to create the HAZ properties in this case as opposed to the PWHT. The weldment was accomplished employing a 2.38 mm ($^3\!/_{32}$ in.), 3.175 mm ($^1\!/_8$ in.), and 3.97 mm ($^5\!/_{32}$ in.) combination for the first three layers. Double-up welding was utilized through the welding process, and the cavity was filled with 3.97 mm ($^5\!/_{32}$ in.) rods from layer three onward. No photographs of this weldment have been included because the coupon configuration was virtually identical to the weldment TC6. Following welding, the weldment was sectioned for mechanical and metallurgical testing after x-ray inspection.

The procedures employed for TC10WR were essentially similar to that of TC7WR, with differences in amperage and weld deposition rate due to section-size differences.

GTAW Repair Weldment TC8WR. Repair weldment TC8WR was performed on a header girth weldment with the GTAW process and was subsequently postweld heat treated. The repair was performed on the lower leg of a T section from the $2\frac{1}{4}$ Cr-1Mo header (Fig. 2), whereas weldments TC9WR and TC10WR were performed on the two upper legs of the header T. A Dimetrics Gold Track II welding system (Liburdi-Diametrics, Davidson, NC) was employed to perform the wall buttering of 7.62 cm (3 in.) deep cavity. Upon completion of the three layers of the weldment, the repair was completed using the SMAW process. The SMAW process was utilized due to the large volume of weld metal required to fill the cavity. All subsequent testing was focused around the GTAW HAZ location. Therefore, the SMAW filler layers did not affect the test results within the HAZ.

4. Results and Discussion

Metallographic examination and mechanical tests were carried out on the repair welded samples. Metallography did not reveal anything unusual, and the results are documented in Ref 1.

4.1 *Tensile Testing*

Tensile tests were performed in duplicate at both room temperature and at 565 °C (1050 °F) using composite 12.8 mm (0.505 in.) diameter tensile tests (centered at the weld fusion line). The test results for degradation level 1 HRH pipe material are provided in Table 2. Examination of TC6 (piping material) test data suggests that almost identical tensile properties are measured for the base metal, service-removed, and weld-repaired conditions at both room temperature and at 565 °C (1050 °F). The temper bead repair for TC7WR produced slightly higher yield strength (YS) properties at room temperature, while producing slightly lower values at elevated temperature compared to the PWHT repair TC6WR. All other tensile properties (tensile, elongation, and reduction of area) for this weldment appeared consistent for the base metal (BM), service-removed (SR), and weld-repaired (WR) conditions. No adverse effects due to either type of weld repairs on the ductility of the steel were observed.

In the case of level 2 degradation, larger variability in properties could be readily noted. First, the effect of the more severe degradation was apparent primarily in the 565 °C (1050 °F) YS and tensile strength states for both base metal and exservice welds. For instance, the 565 °C (1050 °F) YS values for the exservice base metal and weld were 134 and 141 MPa (19.5 and 20.5 ksi), respectively, as contrasted to corresponding values of 162 and 159 MPa (23.5 and 23 ksi) for degradation level 1. Similarly, the tensile strength values for the degradation level 2 steel for the exservice base metal and weld at 565 °C (1050 °F) were 32.6 and 33 ksi, respectively, as contrasted to 258 and 272 MPa (37.5 and 39.5 ksi) for degradation level 1 samples. These results demonstrate that the more prolonged exposure in the degradation level 2 samples resulted in decreased tensile and YS values at high temperature. The differences are not so apparent at room temperature. Another explanation could be the flux composition. In one case, basic SMAW is used and in another, acidic SAW is used.

The beneficial effects of weld repairs are also more obvious in the degradation level 2 samples. The benefits are most apparent in the YS values, both at room temperature and at 565 °C (1050 °F). For instance, the YS values at room temperature and

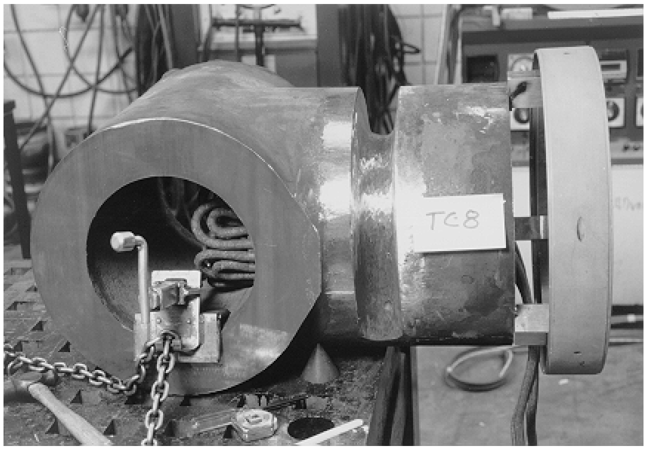
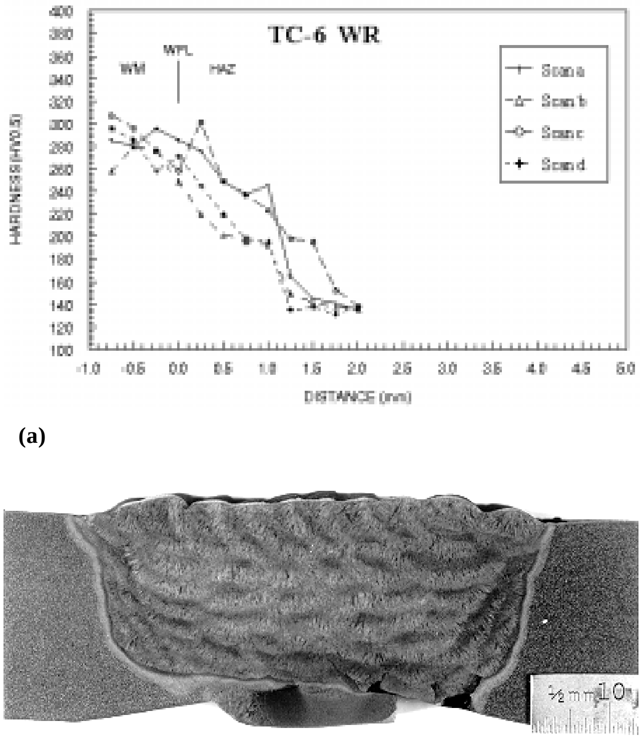


Fig. 2 Weld coupon TC8WR following excavation

Table 2 Tensile properties for base metal, service-removed weld, and weld repair weldments

Specimen designation	Test temperature, °C	0.2% yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %	Reduction in area, %
Degradation level 1					
TC6BM	RT	211	460	29	73.3
TC6SR	RT	217	471	24.5	69.9
TC6WR	RT	225	463	21.7	73.5
TC7SR	RT	221	456	23.8	68.1
TC7WR	RT	250	434	19.8	69.5
TC6BM	565	162	258	38.7	83.4
TC6SR	565	159	272	21.6	77.7
TC6WR	565	154	255	26.2	84.7
TC7SR	565	142	246	33.6	82.2
TC7WR	565	139	234	23.4	81.0
Degradation level 2					
TC8WR	RT	288	529	22.4	71.8
TC9BM	RT	204	448	28.5	67.1
TC9SR	RT	212	450	67.4	67.4
TC9WR	RT	227	452	21.3	72.1
TC10SR	RT	215	465	25.9	69.3
TC10WR	RT	283	461	21.9	71.6
TC8WR	565	164	277	22.2	74.2
TC9BM	565	134	225	41.0	79.6
TC9SR	565	141	231	77.9	77.9
TC9WR	565	165	257	22.9	78.5
TC10SR	565	142	229	31.0	84.1
TC10WR	565	167	249	22.2	80.0

RT, room temperature; BM, base metal; SR, service-removed weldment; WR, weld repaired weldment at 565 °C (1050 °F) increase from 212 and 141 MPa (30.7 and 20.5 ksi), respectively, to 227 and 165 MPa (32.9 and 24.0 ksi) by PWHT repair. The improvements are substantially more pronounced in the temper bead repairs, which increase the room temperature YS from 215 to 283 MPa (31.2 to 41.0 ksi) and the 565 °C (1050 °F) YS from 141 to 167 MPa (20.5 to 24.2 ksi). Changes in tensile strength were insignificant. The improved YS properties noted with both temper bead and GTAW repairs are coupled with slight decreases in ductility as reflected by elongation.



(a)

(b)

Fig. 3 Illustration of a plug sample and microhardness profiles. The profiles for service removed (SR) and weld repaired (WR) conditions are typical of the other SR and WR specimens.

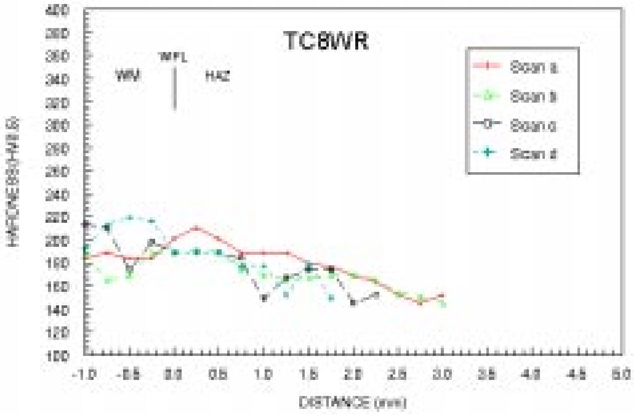


Fig. 4 Microhardness test results for weld repair TC8WR with a macrograph depicting the locations of the microhardness scans

Composite tensile specimen test values were also recorded for a third header repair weldment, TC8WR, as shown in Table 2. The tensile strength of the GTAW (with PWHT) repair was measured to be 528.5 and 272.2 MPa (75.5 and 39.6 ksi) (at room temperature and 565 °C, or 1050 °F). When compared to the SMAW PWHT condition for TC9WR, this amounts to an increase of approximately 70 MPa (10 ksi) at room temperature. The elevated temperature tensile strength was considerably closer with only 14 to 28 MPa (2 to 4 ksi) difference. Similarly, the room temperature YS was measured at 287.7 MPa (41.1 ksi), approximately 70 MPa (10 ksi) higher than the TC9WR. Elevated YS values were determined to be comparable with TC9WR. The improved properties of the GTAW repair are comparable to those of the temper bead repair 10WR.

4.2 Microhardness

Microhardness tests were performed for each of the service-removed girth weldments and repair weldments (PWHT and temper bead). Figure 3 provides an illustration of the microhardness scans beginning within the actual weldment and moving outward through the HAZ and into the actual base material. Four scans were performed for each weldment including scan a and scan d, which were located on opposite sides of each weldment within the upper two-thirds of the through-wall section, and scan b and scan c, located near the root area of the through-wall section. Table 3 lists average values from the four scans for each weld.

All service-removed girth weldments demonstrated essentially flat (uniform) hardness profiles. Specimens TC6SR and TC7SR exhibited a uniform hardness of approximately 150 HV, while TC9SR and TC10SR exhibited a slightly higher uniform hardness of 170 HV. After weld repair, a hardness gradient is established with a peak hardness being reached in the weld (Fig. 3a). The temper bead repairs result in higher peak hardness than the PWHT repairs. For instance, 330 HV results for TC7WR versus 290 HV for TC6WR, and 320 HV results for TC10WR versus 310 HV for TC9WR. In view of the fact that hydrogen embrittlement, stress corrosion, and other environmentally induced failure mechanisms are not important in header/pipe applications, the higher microhardness due to temper bead repairs are not considered significant.

The GTAW repair (with PWHT) resulted in very low, uniform microhardness values, as shown in Fig. 4. The maximum value recorded for this weldment was approximately 200 HV

Table 3 Microhardness profiles for weldments

Specimen designation	Peak hardness in weld	Average hardness of base metal
TC6SR	150	150
TC6WR	290	150
TC7SR	150	150
TC7WR	330	150
TC9SR	170	170
TC9WR	310	180
TC10SR	170	170
TC10WR	320	170
TC8WR	200	180

BM, base metal; SR, service-removed weldment; WR, weld repaired weldment

(500 g load). Comparison of these results with TC9WR (which was also PWHT) suggested that considerably lower hardness values were generated with the GTAW process. Values were 100 to 120 HV less for the GTAW repair.

4.3 Charpy Impact Toughness

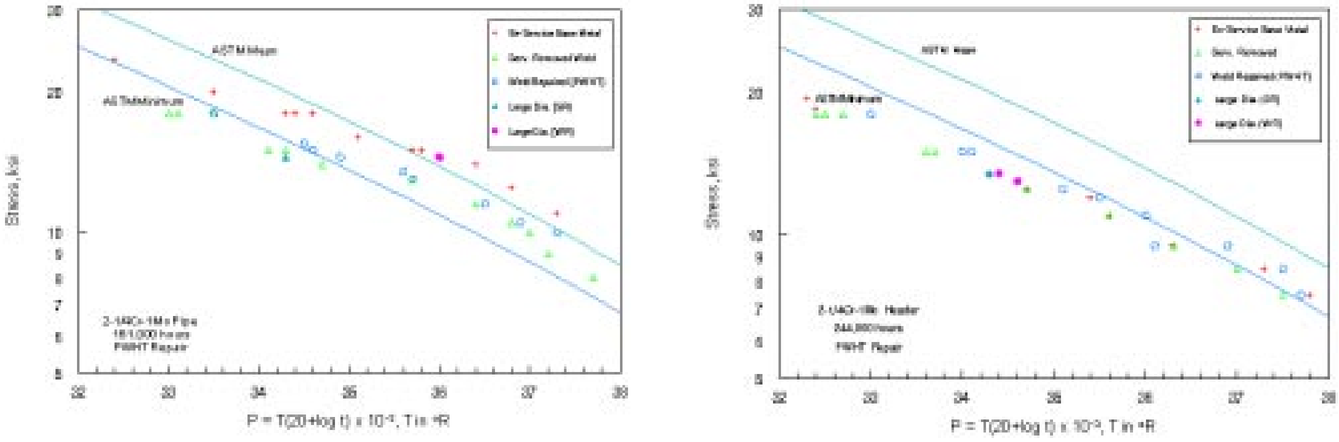
Results of Charpy impact tests using composite specimens with the notch centered at the HAZ are provided for each of the service-removed girth weldments and repair weldments in Table 4. All samples were consistently taken from the midwall (½ *t*) location of the pipe. Three specimens were tested at room temperature for each weldment. In the degradation level 1 pipe samples (TC6, TC7) average toughness values recorded for the two service-removed weldments were 104 and 49.5 J (77.0 and 36.5 ft · lbf). A marked reduction in toughness was observed after the PWHT repair of TC6, and the impact energy decreased from 104 J (77 ft · lbf) to 28.4 J (21 ft · lbf). On the other hand, the temper bead weld repair resulted in an increase of the Charpy impact value from 49.5 J (36.5 ft · lbf) to 187 J (138.7 ft · lbf). Comparison of this value with either of the two service-removed toughness values indicates that the temper bead welding approach produces improved toughness.

In the degradation level 2 samples (TC9, TC10) both service-removed welds had much higher toughness compared to the degradation level 1 samples (117.2 to 124 ft · lbf versus 49.5 J (36.5 ft · lbf for level 1), presumably due to the more prolonged aging and softening effects. Postweld heat treatment resulted in a decrease of toughness from 158 J (117.2 ft · lbf) to 40 J (29.7 ft · lbf), just as previously experienced in the degradation level 1 PWHT sample. Contrary to earlier experience, however, temper bead repair (TC10WR) decreased the toughness from 167 J (124.0 ft · lbf) to 92 J (68.3 ft · lbf). Despite this decrease, the temper bead impact energy value of 68.3 ft · lbf was higher compared to the PWHT specimen value of 40 J (29.7 ft · lbf). The recorded toughness easily exceeds the normally accepted toughness value of 67.5 J (50.0 ft · lbf), 35 mils lateral expansion for pressure vessel materials. It can, therefore, be concluded that for both degradation levels, temper

Table 4 Results of Charpy impact tests at room temperature 35 °C (63 °F)

Weldment	Condition	Impact energy at room temperature, average J (ft · lbf)	Shear, average %	Lateral expansion, average mm (mils)
Degradation level 1				
TC6BM	Base	122 (89.7)	41.7	2.09 (82.3)
TC6SR	…	104 (77.0)	45.7	1.50 (59.0)
TC6WR	PWHT Repair	28 (21.0)	15.0	0.51 (20.0)
TC7SR	…	49 (36.5)	30.0	0.83 (32.7)
TC7WR	TB Repair	188 (138.7)	100.0	2.11 (83.0)
Degradation level 2				
TC8WR	PWHT Repair	75 (55.2)	46.7	1.24 (48.7)
TC9BM	Base	69 (50.7)	38.3	1.68 (66.3)
TC9SR	…	159 (117.2)	91.3	1.98 (78.0)
TC9WR	PWHT Repair	40 (29.7)	8.3	0.83 (32.7)
TC10SR	…	168 (124.0)	97.3	2.20 (86.7)
TC10WR	TB Repair	93 (68.3)	40.0	1.58 (62.3)

BM, base metal; SR, service-removed weldment; WR, weld repaired weldment



(a) **(b)**

Fig. 5 Larson-Miller rupture data plots for TC6 and TC9 with ASTM reference curve for annealed 2¼Cr-1Mo steel. Figure shows the effect of degradation level (a) 1 and (b) 2. (Note: 1 ksi = 6.89 MPa) bead repairs produced improved toughness relative to PWHT repairs. The GTAW repairs resulted in Charpy impact energy levels approaching those of the temper bead repair.

4.4 Creep Rupture Tests

All base metal specimens were tested to determine the level of degradation that the steel had experienced due to service exposure. Ex-service weldments (SR) and repair welds (WR) were tested using composite specimens taken at the ½ *t* location of the pipe (i.e., midwall). Specimens of 6.35 mm (0.25 in.) diameter were used for most of the tests, while some tests were conducted on 9.05 mm (0.75 in.) diameter specimens to evaluate specimen size effects. The majority of the tests employed both varying stress and temperature, and the results were plotted as a function of the Larson-Miller parameter, i.e., $P = T(20 + \log t_r)$, where T is expressed in degrees Rankine, 20 is an empirical constant, and the time to rupture, t_r, is expressed in hours. The Larson-Miller parameter, by definition uses units of ksi, °R, and hours for stress, temperature, and time, respectively. These tests were conducted at 566, 593, and 621 °C (1050, 1100, and 1150 °F) at stress levels in the range of 55 to 138 MPa (8 to 20 ksi). In addition, a limited number of isostress tests were conducted in which the stress was held constant at 54 MPa (7.8 ksi), varying the temperature in the range 621 to 676 °C (1150 to 1250 °F).

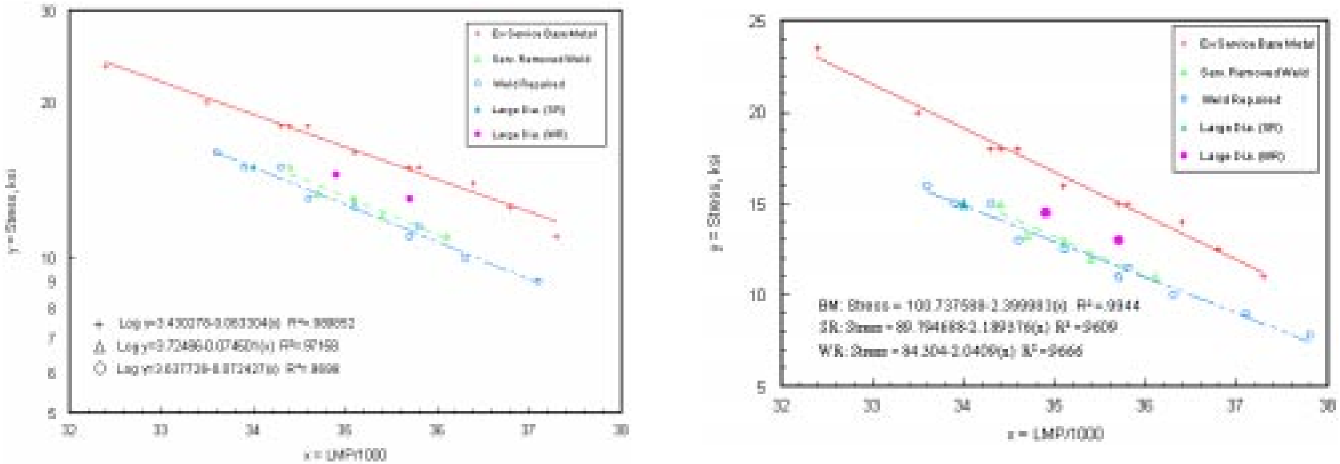
Larson-Miller plots for TC6 and TC9 are shown in Fig. 5 (a) and (b) against the reference curve for annealed 2¼ Cr-1Mo steel published by Smith for ASTM (Ref 1), principally to contrast the effect of the degradation level. In the degradation level 1 material TC6, the base metal properties fluctuate about the mean while the SR weld properties lie between the mean and the minimum. In the degradation level 2 material TC9, the base metal and weldment properties are clearly below the ASTM minimum curve, as is to be expected from the service history. In both cases the weld properties are below that of the respective base metal, while weld repair seems to restore the properties to a level approximately that of SR weld in TC6 and to a level on a par with base metal in TC9.

To compare BM, SR, and WR conditions for each weld, Larson-Miller plots were prepared separately for each weld, using both stress and log stress as the ordinate. In general, use of stress resulted in a higher degree of correlation than the use of log stress. Larson-Miller plots and the pertinent equations are illustrated in Fig. 6. It is difficult to compare different welds and different conditions from these plots because relative positions of the lines vary with stress due to change in slope. The only way to compare performance is to

Table 5 Estimated remaining lives of exservice base metal, weld, and weld repairs for 2¼Cr-1Mo steel under assumed design conditions of 538 °C (1000 °F) and 55 MPa (7.8 ksi) stress using Larson-Miller parametric extrapolation

Weld identification	Condition of weld repair	Base metal, h	SR weld, h	WR, h	Ratio WR/SR
Degradation level 1					
TC6	SMAW-PWHT	3.4×10^6	1.02×10^6	1.63×10^6	1.6
TC7	SMAW-TB	Assumed same as TC6	3.65×10^5	4.74×10^5	1.3
Degradation level 2					
TC8	GTAW-PWHT	Assumed same as TC9		4.31×10^5,	
TC9	SMAW-PWHT	3.76×10^5	2.95×10^5	4.98×10^5	1.7
TC10	SMAW-TB	Assumed same as TC9	3.39×10^5	6.93×10^5	2.0

SR, service-removed weldment; WR, weld repaired weldment



(a)

(b)

Fig. 6 Larson-Miller representation of results for TC7, degradation level 1 material in the base metal (BM), service removed (SR), and weld repair (WR) (temper bead) conditions using (a) log stress and (b) stress. (Note: 1 ksi = 6.89 MPa) compare remaining life as extrapolated to some select design condition.

Table 5 summarizes the estimated remaining lives of various welds under assumed design conditions of 538 °C (1000 °F) and 55 MPa (7.8 ksi). The same data are plotted as bar charts for easy visualization in Fig. 7. The estimated rupture hours are all quite high. Whether these high values are due to inherent errors in the Larson-Miller extrapolation procedure or not is unclear. On a relative basis, however, it can readily be seen that the service-exposed weldments have shorter lives compared to the service-exposed base metal. Weld repair, however, seems to always lengthen the lifetimes compared to the service-exposed weldments. The effect is particularly noteworthy in the degradation level 2 material, where the postweld repair properties exceed those of the base metal.

In the service-exposed condition, the performance of even adjoining girth welds for a given degradation level (e.g. TC6SR versus TC7SR, or TC9SR versus TC10SR) seems to be variable presumably due to differences in initial fabrication. Due to the scatter in the starting condition prior to weld repair, the performance of temper bead repairs cannot be directly compared with that of the PWHT repairs. Based on the ratio of remaining life of the weld-repaired condition to the service-removed condition for a given weld (i.e., the improvement factor due to weld repair), the temper bead repair to TC10 seems marginally better than the PWHT repair to TC9. On the other hand, the performance of temper bead repair TC7 seems to be marginally inferior to that of the PWHT repair TC6.

4.5 Isostress Rupture Testing

Extensive data in literature have shown that accelerated tests in which acceleration is achieved by increasing temperature rather than stress obey the life-fraction rule for creep damage and, therefore, lead to more valid extrapolations (Ref 2-6). This has encouraged widespread use of the isostress method that was first explored and applied by Stubbe and van Melsen (Ref 3) nearly 20 years ago and detailed by Hart (Ref 2). The method provides an estimate of remaining service life by extrapolation of rupture time data, t_r, to the service temperature from a series of temperature-accelerated tests (test temperatures, T, above the service temperature) conducted on the post-service material. In practice, it has been shown that isostress rupture life extrapolated on a T-log t_r basis approaches the isothermally determined life at the operating temperature within a factor of 2 (Ref 4-6). The excellent correlation between the extrapolated rupture life from isostress tests and the actual life obtained in isothermal tests has been demonstrated by, for example, Beech et al. (Ref 5).

In view of the successful application of isostress rupture testing in industry, tests were conducted using composite rupture specimens on all the WR samples at a fixed stress of 55 MPa (7.8 ksi) at temperatures of 621, 648, 662, and 676 °C (1150, 1200, 1225, and 1250 °F).

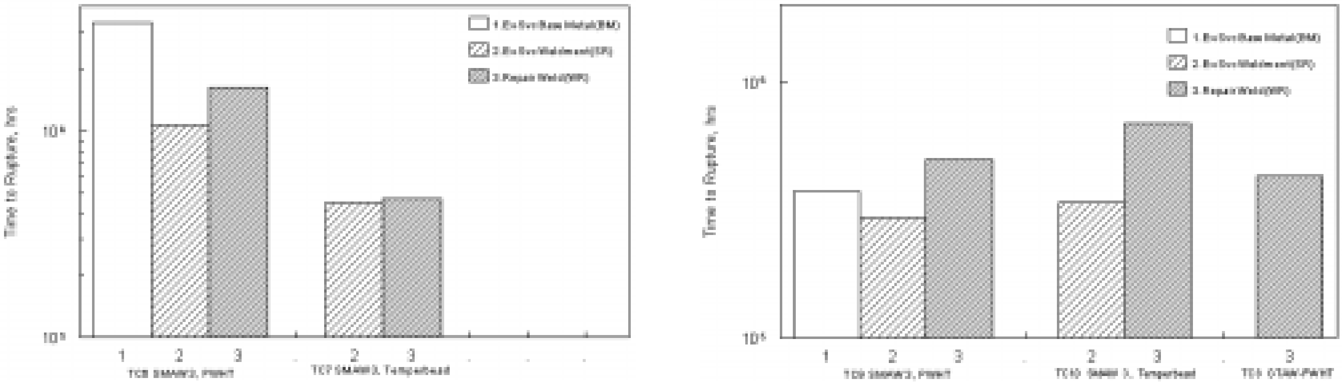
Figure 8 illustrates the T or $1/T$ versus log t_r correlations for the various TC10WR samples. Good linear fits were obtained for all the WR samples for use of both $1/T$ and T on the y axis. Note that the equation shown in Fig. 8 uses the natural logarithm function (ln x) and not log x. The correlation coefficients are slightly higher for the T versus log t_r fit, making this the preferred extrapolation method.

Using the correlations developed, the remaining life under assumed design conditions of 538 °C (1000 °F) and 55 MPa (7.8 ksi) can be calculated. Results of this calculation are shown in Table 6 in comparison with those obtained by stress versus Larson-Miller parameter correlations described earlier. This comparison again shows the isostress extrapolation techniques to result in lower estimates of remaining lives compared to Larson-Miller extrapolations. The lowest estimates for re-

Table 6 Estimated remaining life in hours of repair weldments at 538 °C (1000 °F) and 54 MPa (7.8 ksi) based on three different extrapolation procedures

Weld identification	Larson-Miller	Isostress, 1/*T*	Isostress, *T*
TC6WR	1,630,000	573,265	255,812
TC7WR	474,680	503,177	230,390
TC9WR	498,000	278,384	133,598
TC10WR	693,000	280,517	139,559
TC8WR	434,000	369,273	167,521

WR, weld repaired weldment



(a) **(b)**

Fig. 7 Remaining life at design conditions of 538 °C (1000 °F) and 55 MPa (7.8 ksi) estimated from linear stress versus Larson-Miller parameter extrapolation for 2¼ Cr-1Mo steel. (a) Degradation level 1; (b) degradation level 2 maining life are obtained using a log t_r versus T extrapolation. It is also very encouraging to note that the temper bead repair and PWHT repair results are nearly identical at both degradation levels (i.e., TC6WR versus TC7WR, and TC9WR versus TC10WR) when either of the isostress extrapolation procedures are used. The lowest value obtained of 139,559 h still represents nearly 18 years of additional service. Another interesting result is the emergence of the GTAW repair TC8WR as an improvement over the other SMAW repairs. Even the lowest value for the temper bead repairs, however, amounts to a remaining life of 4.74×10^5 h or 60 years (assuming 8000 h/year) and is deemed quite adequate. The data obtained in this project show that temper bead repairs have no adverse effects on rupture ductility.

An interesting aspect of the rupture is the failure location. In the degradation level 1 service-returned samples (TC6SR and TC7SR), the base metal had not sufficiently degraded to the point where failures could occur in the base metal. The weak link and, hence, the failure location was the weld metal. After performing weld repair, the weld metal was no longer the weak link. Failure was shifted to base metal in the TC6WR and TC7WR samples. In the degradation level 2 samples (TC9, 10SR) even the initial failures occurred in the base metal, presumably because of the degradation that occurred in the base metal. Weld repair had no effect on the failure location.

4.6 Effect of Specimen Size

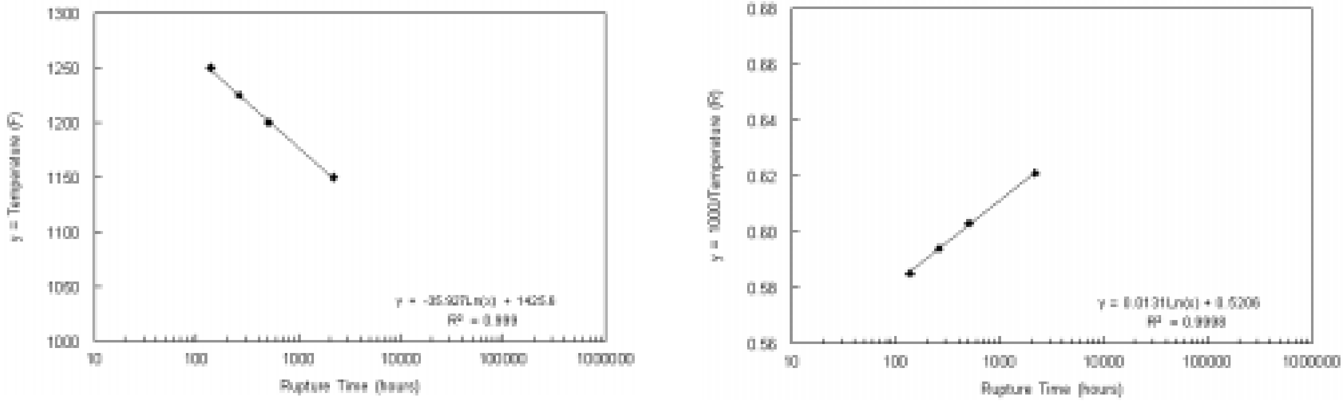
A comparison of stress rupture lives obtained for 6.35 mm (0.25 in.) diameter specimens and the 19 mm (0.75 in.) diameter specimens at 565 °C (1050 °F) at various stress levels is shown in Table 7. For both TC6 and TC7 in the SR weldment, the larger diameter specimens showed shorter rupture lives. Correspondingly, the failure location shifted from weld metal in the small specimen to base metal in the large specimen. After weld repair, the weld metal was no longer a weak link, and all failures, in the small and in the large specimens, occurred in the base metal. In this condition, the large specimens consistently showed substantially longer remaining lives. This is encouraging, because the component lives in the weld-repaired condition will well exceed those estimated from the Larson-Miller and isostress extrapolations discussed earlier.

In the case of the degradation level 2 specimens (i.e., TC8, 9, and 10), considerable degradation of the base metal had occurred so that even in the service-removed welds the weak link was the base metal. Weld repair in these cases resulted in continued failures in the base metal. Hence, specimen size effects were only marginal and not systematic. Specimen size effects thus seem to be a function of the level of service degradation prior to repair.

Table 7 Effect of specimen size on creep rupture life at 565 °C (1050 °F) for four sets of weldments

Specimen designation	Test stress, MPa (ksi)	6.35 mm (0.25 in.)		19 mm (0.75 in.)	
		Life, h	Failure location	Life, h	Failure location
TC6SRL-1	102 (14.5)	955	Weld	558	Base
TC6WRL-1	102 (14.5)	1758	Base	7000	Base
TC6WRL-2	108 (15.5)	672	Base	2870	Base
TC7SRL-2	108 (15.5)	519	Weld	318	Near HAZ
TC7WRL-1	91 (13.0)	1295	Base	4292	Base
TC7WRL-2	102 (14.5)	448	Base	1316	Base
TC9SRL-2	94 (13.5)	704	Base	538	Base
TC9WRL-1	94 (13.5)	1112	Base	607	Base
TC9WRL-2	91 (13)	1509	Base	787	Base
TC10SRL-1	91 (13)	445	HAZ	913	Base
TC10WRL-1	94 (13.5)	1112	Base	902	Base

SR, service-removed weldment; WR, weld repaired weldment; TC6 and TC7, degradation level 1; TC9 and TC10, degradation level 2



(a)

(b)

Fig. 8 Results of isostress rupture tests on TC10WR at 7.8 ksi using (a) T and (b) $1/T$

5. Conclusions

Weld repairs were performed to girth weldments previously exposed in service to two levels of degradation by use of SMAW and GTAW repairs with PWHT and use of temper bead repairs. The different welds were evaluated prior to and after weld repair to study the effects of degradation on repairability, the effectiveness of temper bead repairs, and the remaining life achievable by weld repair. Results of these evaluations show the following:

- *Quantification of prior degradation:* Extended exposure of 2-¼Cr-1Mo steel in service caused degradation of mechanical properties of the girth welds without evidence of creep cavitation damage. Degradation is not so apparent after a 538 °C (1000 °F)/161,000 h (degradation level 1) exposure. In the header exposed to 565 °C (1050 °F)/244,000 h (degradation level 2), degradation is more pronounced, and the YS and tensile strength for both base metal and weld at 565 °C (1050 °F) are decreased compared to those for the degradation level 1 materials. The creep rupture strength becomes substantially lower for both base metal and for the exservice weld compared to that for the degradation level 1 material, but even the lower values of remaining life obtained for the more severely degraded exservice weld correspond to nearly 2.95×10^5 h or nearly 37 years, under assumed design conditions of 538 °C (1000 °F) and 55 MPa (7.8 ksi) using Larson-Miller parametric extrapolation. This is very encouraging from a plant life extension point of view.
- *Efficacy of weld repair:* Weld repairs to the degraded exservice welds resulted in restored or improved tensile and creep properties. The degree of improvement was a function of the prior condition. Improvements to tensile properties and creep rupture properties due to weld repair were marginal for the less severe degradation level 1 welds but became much more apparent for the degradation level 2 welds. In the latter case, weld repairs (WR) consistently showed higher yield strength at both room temperature and at 565 °C (1050 °F) and higher tensile strength at 565 °C (1050 °F), compared to the exservice weld prior to repair. The rupture life values for the weld-repaired samples consistently exceeded the exservice base metal properties. Nevertheless, the projected remaining life after weld repair was considerably less for the header material with more severe prior degradation. These remaining lives still provided the promise of considerable life extension by weld repair. The tensile properties of all weld repairs met ANSI B31.1 code requirements.
- *PWHT effects on toughness:* Shielded metal arc welding and postweld heat treatment repairs resulted in substantial decreases in the room temperature impact energy of ex-service weldments. Results of temper bead repairs were mixed. In degradation level 1 samples, temper bead repairs significantly increased the impact energy, while in the degradation level 2 samples, a decrease in impact energy was noted compared to the exservice weldment. In all cases, however, the temper bead repairs consistently produced higher impact toughness compared to the corresponding SMAW-PWHT repairs.
- *Effect of temper bead repairs:* The effectiveness of temper bead repairs relative to SMAW-PWHT repair was found to be a function of prior degradation. In degradation level 1 material, tensile properties for the two types of repairs were nearly the same, while for the more severely degraded material, the room temperature yield strength was higher for the temper bead repair by nearly 70 MPa (10 ksi) compared to that for the PWHT repair. Based on Larson-Miller parametric extrapolation, the estimated creep rupture life improvement under design conditions of 538 °C (1000 °F), 55 MPa (7.8 ksi) relative to the pre-repair condition of the weld was slightly lower or higher for the temper bead repair in comparison to the PWHT repair, depending upon the degradation level. Isostress test data extrapolation, however, suggests the performance of both types of repairs to be identical.
- *Effect of extrapolation procedure on remaining life:* Isostress rupture tests, in which only test temperature is varied, result in shorter rupture lives compared to Larson-Miller parameter based tests, under similar test conditions. Estimated remaining lives under design conditions of 538 °C (1000 °F) and 55 MPa (7.8 ksi) therefore vary with the type of extrapolation procedure used. The most conservative (lowest) values are obtained for isostress rupture test data extrapolations plotting log t_r versus T. Even with this conservative procedure, both PWHT and temper bead repairs result in estimated remaining life of nearly 30 years (230,000 to 255,000 h) for the degradation level 1 material and nearly 18 years (133,000 to 139,000 h) for the degradation level 2 material. Actual component lives can exceed these values due to their larger section size, because results of this study also show a threefold to fourfold increase in remaining life due to an increase of specimen size from 6.35 to 19 mm (0.25 to 0.75 in.), especially in the degradation level 1 steel. No significant loss of stress rupture ductility occurred in temper bead repairs compared to PWHT repairs.
- *Microhardness profiles:* Microhardness profiles showed uniform and low values of hardness in the range of 150 to 170 HV at both degradation levels in the exservice welds. Following weld repair, steep hardness gradients were observed with peak hardness values in the weld metal. The peak hardness values are 10 to 40 HV points higher in temper bead repairs compared to those of the PWHT repairs (e.g., 330 HV versus 290 HV for degradation level 1 and 320 HV versus 310 HV for degradation level 2).
- *GTAW repairs:* In terms of overall improvements in all the properties studied, the GTAW repairs with PWHT yielded the best results. The tensile properties of these repairs were higher than those of SMAW-PWHT repairs and were comparable to those of temper bead repairs. The microhardness distribution was uniform across the weld, and the actual values of 190 HV were well below the peak values but above the base metal values found in the other repair welds. The room temperature impact toughness was considerably better than SMAW-PWHT repairs and approached that of the temper bead repair. Gas tungsten arc welding and post-

weld heat treatment repairs also resulted in much higher remaining life compared to both SMAW-PWHT and temper bead repairs based on isostress rupture test data extrapolation. Based on Larson-Miller parametric extrapolation, the GTAW-PWHT repair is comparable to the SMAW-PWHT repairs and approaches the temper bead repair.

- *Overall conclusions:* The overall results of this study show that service-aged piping systems can be successfully weld-repaired with or without PWHT and that life extension by several decades is achievable under design conditions. Although the service-returned girth weldments evaluated here did not exhibit cavitation-type creep damage, results of other studies reviewed elsewhere (Ref 7) confirm that as long as material with prior creep-cavitation damage of any type is completely excavated and operating stresses and temperatures do not exceed design values, weld repairs can successfully extend the life of piping systems by several decades.

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