QUARTERLY REPORT

Project WP#339: Structural Significance of Mechanical Damage

For Period Ending: May 31, 2009

Contract No: DTPH56-08-T-000011

Prepared For: United States Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Office of Pipeline Safety

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ELECTRICORE

PRCI LEADING PIPELINE RESEARCH

Milestone and Deliverable Accomplishments this Reporting Period

Task No.	Task	Scheduled Completion Date	Completed Date	Milestone
2	Purchase & Characterize Pipe Material	Estimated 09/30/2009	Ongoing	
3	Literature Review	06/30/3009	Ongoing	MS
4	Testing of Dents on Welds and Corrosion Features	08/30/2009	Ongoing	MS
5	Testing of Dents with Gouges	5/31/2010	Ongoing	MS
6	Demonstration of Mech. Damage Model Performance	11/30/2009	Not Yet Started	MS
7	Industry Workshop	5/31/2010	Not Yet Started	
8	Project Management and Reporting	5/31/2010	Ongoing	MS

Technical Status

Technical activities undertaken through the fourth quarter focused on the following tasks:

Task 2: Purchase & Characterize Pipe Material
Task 4: Testing of Dents on Welds and Corrosion Features
Task 5: Testing of Dents with Gouges

A summary of the technical status and results or conclusions to date are presented below for each of these tasks.

The technical group for this program has maintained close communication to ensure program coordination. Issues of concern in the program have been forwarded to PRCI and DOT for their consideration.

Task 2: Purchase & Characterize Pipe Material

Technical Status

The entire program comprises 3 different pipe steels:

- Two modern IPSCO pipes manufactured during 2005/2006 called:
  - Pipe 1
  - Pipe 2
- Pipe 3 is planned to be older steel, either a former operating/in-service vintage pipe from one of PRCI's member companies or a manufactured pipe that replicates vintage pipe properties. The source of Pipe 3 remains to be established.

A potential source has been identified for the manufacture of pipe representing older/vintage pipes, with material properties replicating the observed lower toughness of 1950's or 1960's era linepipe, and cost/schedule data have been collected. The technical group for the project is evaluating the benefits of a manufactured option to avoid the variability introduced by unknown operations (i.e., pressure cycling over time) and is coordinating the final decision with PHMSA.

GDF SUEZ has received three pipes of 11.8 meters length of Pipe 1 and two pipes of 11.8 meters length of Pipe 2. These pipe steels are current steels, one specified API X52 grades and the second API X70 grade. The diameter of all pipes is 24'' and the thicknesses are 7.9mm for the X52 grade (Pipe 1) and 9.0mm for the X70 grade (Pipe 2). The pipes were manufactured by IPSCO with the ERW process.

In the previous quarterly reports, GDF SUEZ presented material characterization results for Pipes 1 and 2:

- Tensile properties in longitudinal and transverse directions;
- Charpy V impact values in different directions at room temperature;
- Toughness J Curve;
- Size of slip bands (Extra-work)

In the 4rd Quarterly period, the effect of pre-strain on toughness (J Curves) was investigated for Pipe 1.

Task 3: Literature Review

Technical Status

Any new information on pre-strain effect on toughness and on realistic defects from field feedback will be captured as it becomes available from other sources.

The literature review has identified a number of sources of potential cyclic fatigue dent assessment techniques. These have been gathered and a thorough review and comparison of the techniques is underway with the goal of using a select number of techniques in Task 6 to demonstrate the performance of each in predicting the fatigue lives of the experimental specimens.

Task 4: Testing of Dents on Welds and Corrosion Features

Technical Status

The testing of plain dents for pipe materials 1 and 2 has been completed. The detailed test matrix for dents on welds has been finalized (see Table below) and the testing has commenced with completion of the first four specimens.

Dent on Girth Welds Testing Matrix

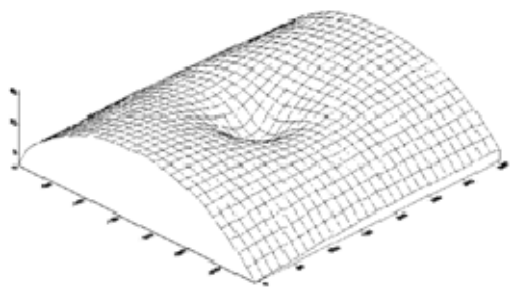
	Pipe	Indenter	Initial Dent	Dent	Interacting	Initial Pressure	Second Pressure	Cyclic Pressure	Weld Seam
Specimen #		Diameter	Depth	Condition	with	Cycle	Cycle	Range	Location
		(in)	(%)			(%SMYS)	(%SMYS)	(%SMYS)	
21	1	2	5	R	Girth Weld	100%	80%	10%-80%	Shoulder
22	1	2	5	R	Girth Weld	100%	80%	10%-80%	Shoulder
23	2	4	10	R	Girth Weld	100%	80%	10%-80%	Shoulder
24	2	4	10	R	Girth Weld	100%	80%	10%-80%	Shoulder
25	1	2	15	U	Girth Weld	100%	80%	10%-80%	C.L.
26	1	2	15	U	Girth Weld	100%	80%	10%-80%	C.L.
27	1	2	15	U	Girth Weld	100%	80%	10%-80%	Shoulder
28	1	2	15	U	Girth Weld	100%	80%	10%-80%	Shoulder

29	1	4	15	U	Girth Weld	100%	80%	10%-80%	Shoulder
30	1	4	15	U	Girth Weld	100%	80%	10%-80%	Shoulder
31	2	2	15	U	Girth Weld	100%	80%	10%-80%	Shoulder
32	2	2	15	U	Girth Weld	100%	80%	10%-80%	Shoulder
33	2	4	15	U	Girth Weld	100%	80%	10%-80%	Shoulder
34	2	4	15	U	Girth Weld	100%	80%	10%-80%	Shoulder
35	2	4	15	U	Girth Weld	100%	80%	10%-80%	C.L.
36	2	4	15	U	Girth Weld	100%	80%	10%-80%	C.L.

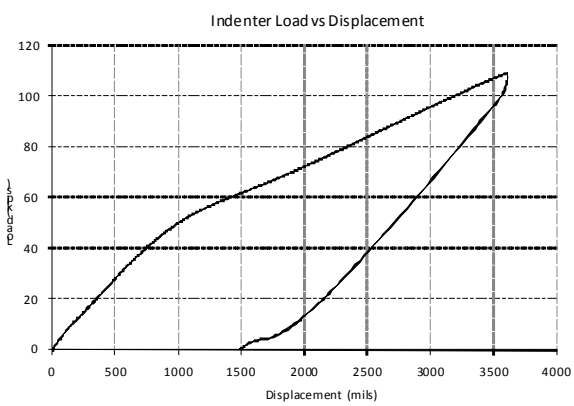
Development of the detailed test matrix for the dents on corrosion features, including the size, shape, and location of the simulated corrosion features is currently ongoing. A finalized test matrix will be provided to the technical group for feedback prior to starting the testing.

Results and Conclusions

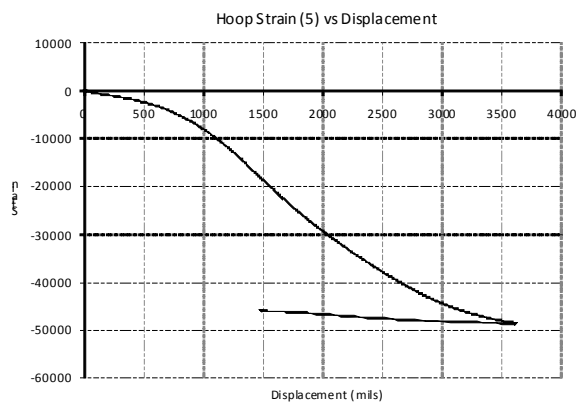
A sample of the detailed results of the testing to date is shown below and includes detailed maps of the dent shapes, the indentation force versus displacement for each specimen, and the internal pressure versus the measured pipe wall strains.



Detailed Scan of Post Test Dent Shape

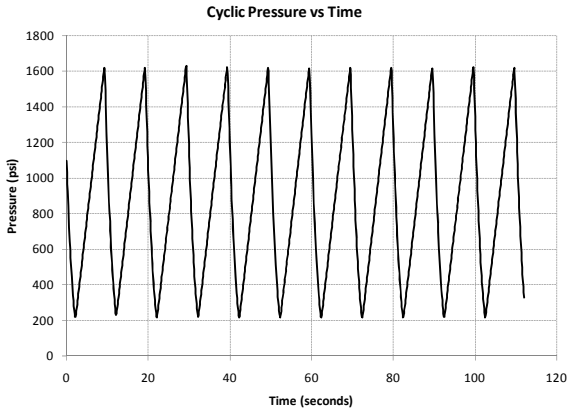


Indenter Load vs Displacement

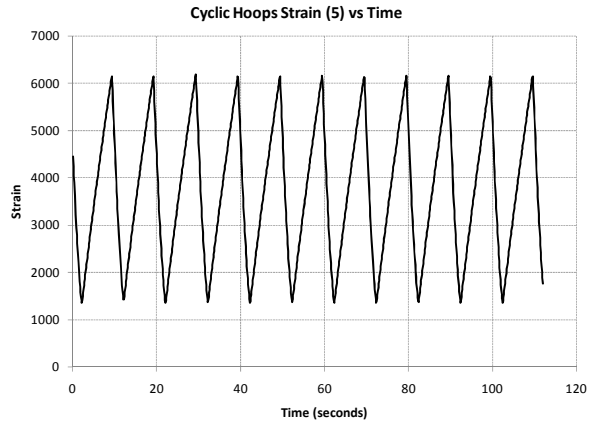


Hoop Strain @ Gauge 5 vs Displacement

Indentation Stage



Cyclic Internal Pressure vs Time



Cyclic Hoop Strain @ Gauge 5 vs Time

Cyclic Pressure Testing

Task 5: Testing of Dents with Gouges

Technical Status

GDF SUEZ is in charge of the creation, characterization, burst test and fatigue test of realistic combined defects, i.e., "dents with gouges", following the program described in the next table:

The defects are identified by three characters **x.y.z.** which are numbers:

- **x**.y.z. : **x** identifies the **Pipe x** material which can be in this program, 1, 2, or 3;
- x.**y**.z. : **y** defines the **type of dent and gouge defect** characterized by its geometry notably in terms of dent depth and length and gouge depth and length. In this program, the value of y can be in the range of 1 to 3, this program considering a maximum of three different kinds of defects per pipe material.
- x.y.**z.** : **z** is the **number of defect in the defined type of defect**. There are three similar defects per type of defect. The number 1 is for a detailed geometrical, mechanical and metallurgical in-depth defect characterization after its creation. Number 2 is a similar defect for the burst test to evaluate the defect behavior of under monotonic pressure load and number 3 is a similar defect for the fatigue test to evaluate the defect behavior under cyclic variation of the internal pressure.

In the previous quarterly reports, the following results were presented:

- Creation conditions and results for defects 1.1.1, 1.1.1b, 1.1.2, 1.1.3, 1.2.1, 1.2.2, 1.2.3, 2.1.1, 2.1.1b, 2.1.2 and 2.1.3
- Burst test conditions and results for defects 1.1.2, 1.2.2 and 2.1.2
- Fatigue test conditions and results for defect 1.1.3,
- Metallurgical Failure Investigation for defects 1.1.2, 1.1.3 and 1.2.2

This report presents:

- Fatigue test conditions and results for defect 1.2.3,
- Fractographic Investigation of defect fatigue failure 1.1.3,
- Surface residual stresses of defects 1.1.1b and 1.2.1b.

The table below summarizes the progress of the study on "Dent and Gouge" defects from the beginning. The background color code is the following:

- White: Defects not yet created
- Yellow: Defects already created but not yet metallurgically investigated or submitted to Burst or Fatigue tests
- Green: Defects completed

PR 305, pipe 1 & pipe 2	MD 4-1					DOT	
Pipe number	**Pipe 1** (current steel X52)			**Pipe 2** (current steel)		**Pipe 4** (older steel)	
Defect type agreed with Project team	Type 1	Type 2	Type 3	Type 1 or 2	Type 2 or 3	Type 1 or 2	Type 2 or 3
Defect 1: Detailed characterization	Defect 1.1.1b	Defect 1.2.1b	*Defect 1.3.1*	Defect 2.1.1	*Defect 2.2.1*	*Defect 4.1.1*	*Defect 4.2.1*
Defect 2: Burst test	Defect 1.1.2	Defect 1.2.2.	*Defect 1.3.2*	Defect 2.1.2.	*Defect 2.2.2*	*Defect 4.1.2*	*Defect 4.2.2*
Defect 3: Delayed failure	Defect 1.1.3	*Defect 1.2.3.*	*Defect 1.3.3*	*Defect 2.1.3*	*Defect 2.2.3*	*Defect 4.1.3*	*Defect 4.2.3*

Results and Conclusions

- ***Task 2: Material Characterization – Pre-strain effect on toughness of pipe 1***

The pre-strain effect on toughness was studied on pipe 1 for three pre-strain levels: 0%; around 5%; around 10%.

The toughness values were determined for the T-L configuration (Figure 1) by J-Curves applying the multiple specimens method and using SENB specimens (Figure 2).

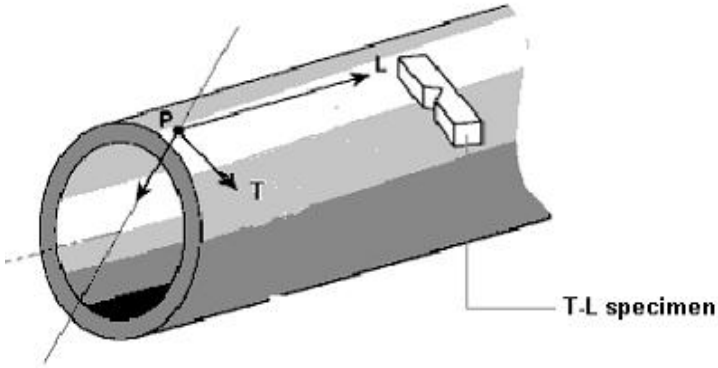


Figure 1: T-L configuration

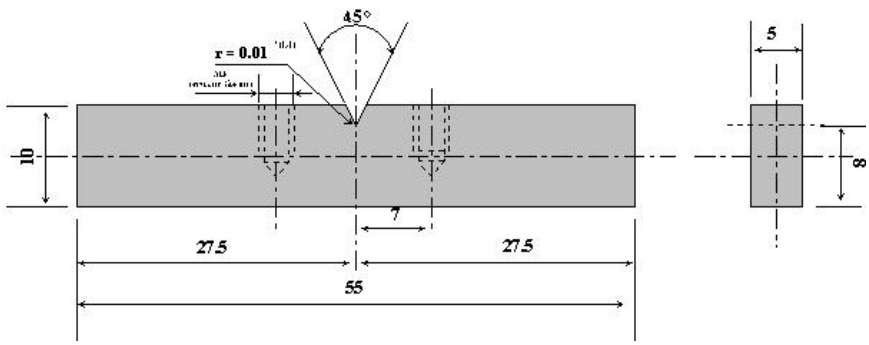


Figure 2: SENB specimen

Full pipe thickness curved strips oriented in the transverse direction and equipped with strain gauges on each side (internal and external) were taken from pipe 1 and flattened by compression (Figure 3).

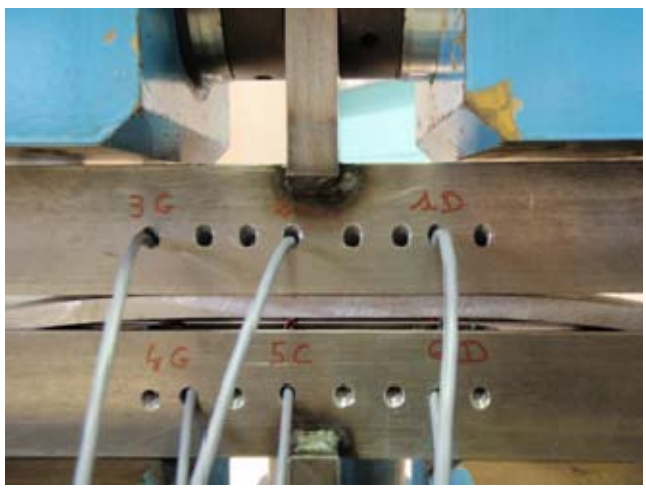


Figure 3: Compression flattening of strip specimen

The maximum strains recorded by the gauges were in the range of [1%, 2%] in tension (internal side) and compression (external side). Then, the flattened strip specimens were submitted to tensile strain levels up to around 5% and 10% indicated by strain gauges. Finally, six T-L SENB specimens were machined in each pre-strained strip (5% and 10%) to determine J-Curves at pre-strain levels of 5% and 10% and to compare with the reference without pre-strain. The J-Curve results are given in Figure 4.

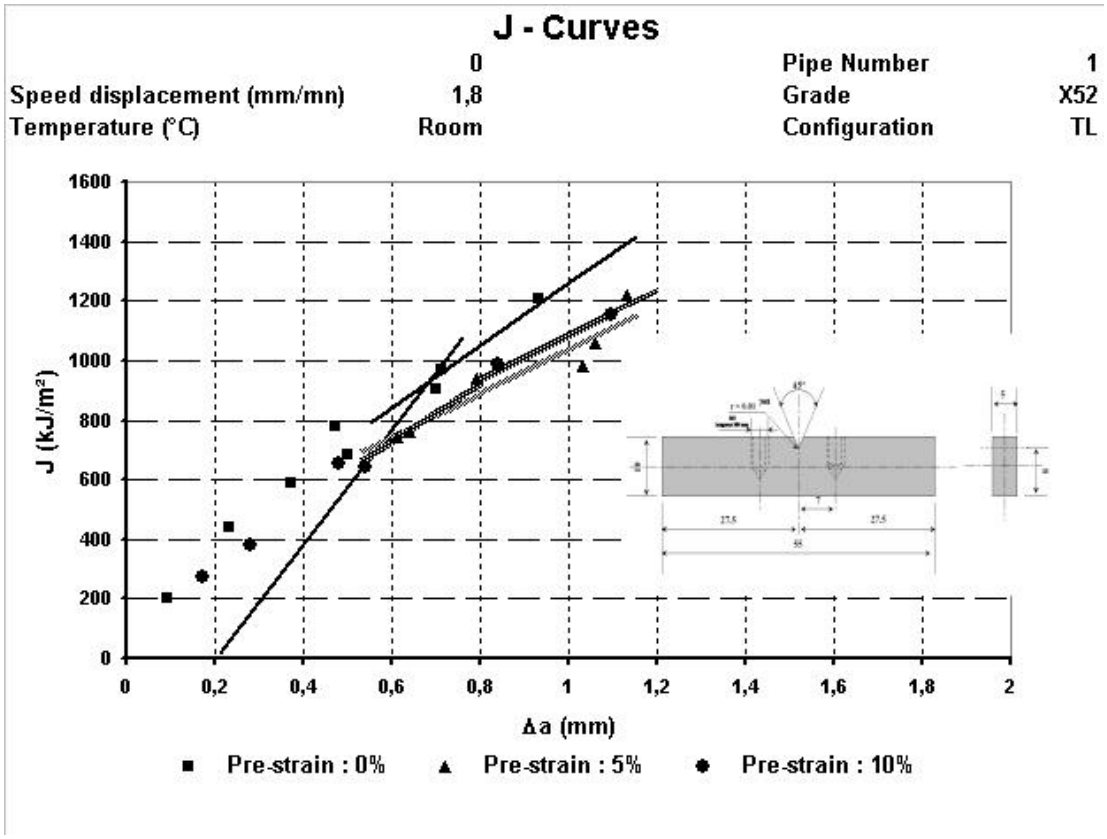


Figure 4: Pipe 1 toughness for pre-strain levels 0%, 5% and 10%

The toughness J_{1C} exhibits very high values of 720 KJ/m² and 668 KJ/m² for pre-strains of respectively 5% and 10%. The decrease of toughness in this range of pre-strain levels [5%, 10%] as compared with the reference toughness value without pre-strain, 929 KJ/m², is less than 30%. This decrease did not change the defect failure behavior up to pre-strain levels of 10% because the steel ductility is still very high.

- ***Task 5: Testing dents with gouges: Fatigue test conditions and results of defect 1.2.3***

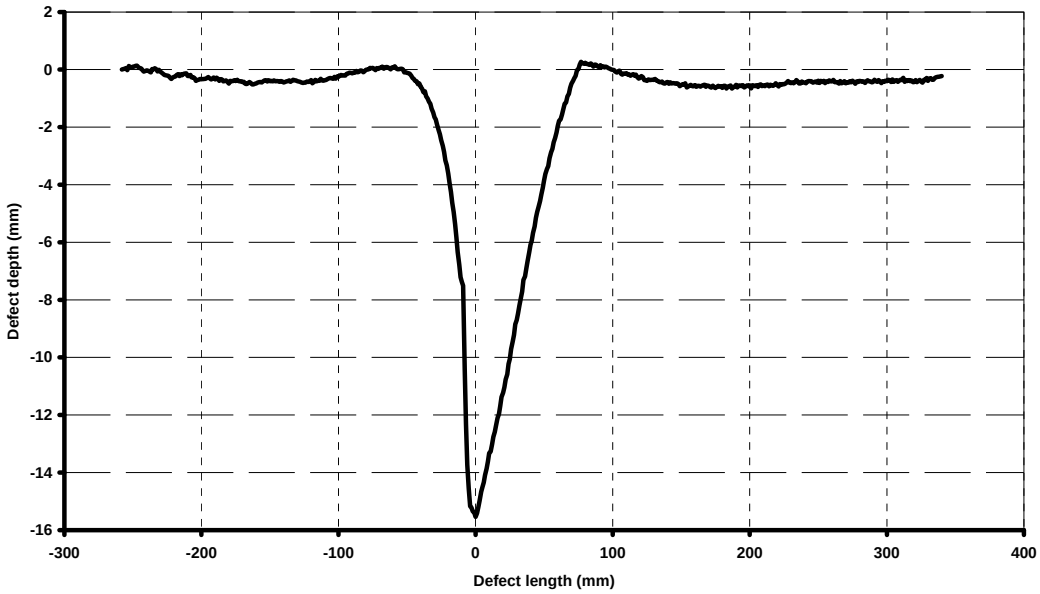
Figures below show the profiles of defect 1.2.3. The maximum relative gouge depth is around 25% of the pipe wall thickness and the maximum residual relative dent depth around 2% of the pipe diameter.

DEFECT 1.2.3

2D longitudinal profile passing by the deepest point of defect (pressure = 0 bar)

Actual load factor : 0.73
Internal pressure during defect creation (bar) : 85
Tooth Type : ESCO

Pipe N° : 1
Diameter (mm) : 609,6
Thickness (mm) : 7.9
Grade : X52

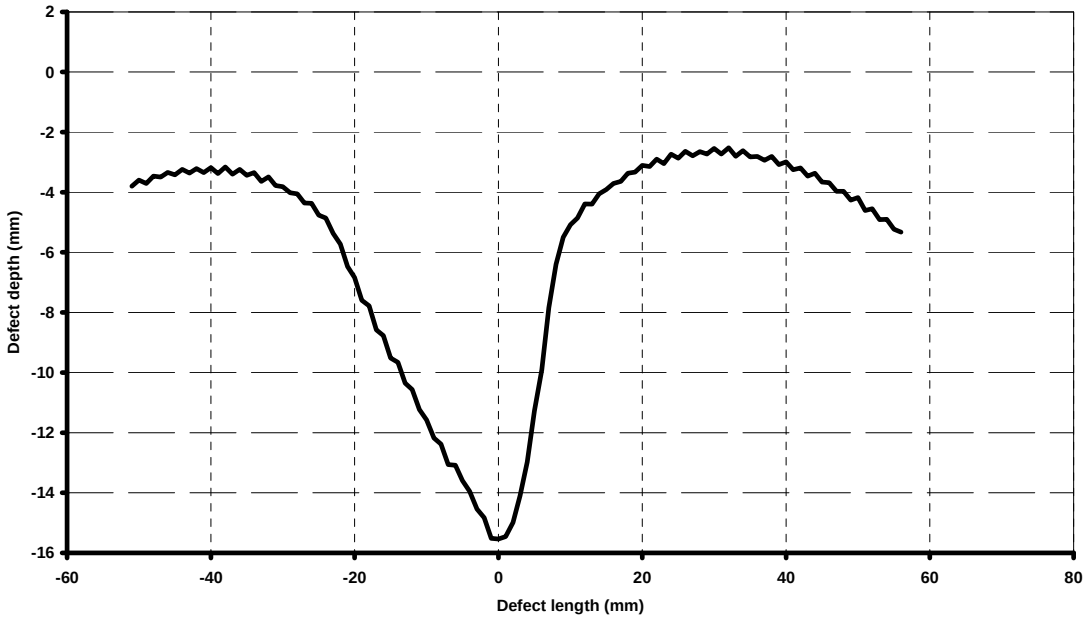


DEFECT 1.2.3

2D circumferential profile passing by the deepest point of defect (pressure = 0 bar)

Actual load factor : 0.73
Internal pressure during defect creation (bar) : 85
Tooth Type : ESCO

Pipe N° : 1
Diameter (mm) : 609,6
Thickness (mm) : 7.9
Grade : X52



The fatigue test of defect 1.2.3 was equipped with the following instrumentation:

- Four rosettes on the edge of the gouge from one end to the other end of defect, which is one more rosette than the three used in previous tests;
- One hoop uni-axial strain gauge in the gouge;
- Strain gauges on the pipe body as reference;
- One potential drop sensor;
- One clip gauge;
- Three displacement sensors – LVDT, two in the gouge and one further away on the pipe body as a reference;
- A camera with targets around the defect;

A sketch of the instrumentation layout around the defect is given figure 5.

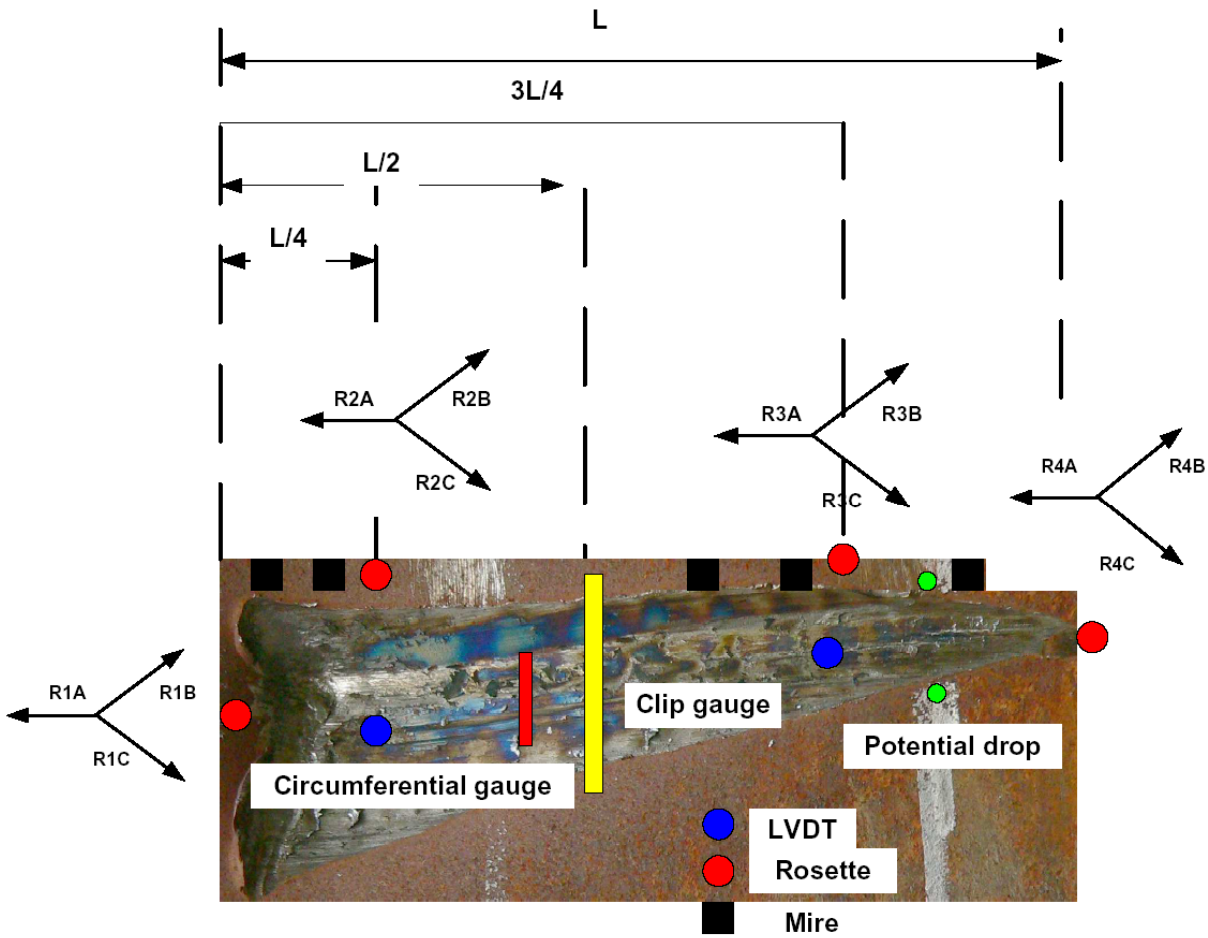


Figure 5: Fatigue Instrumentation of defect 1.2.3

A photo of the instrumentation is provided in Figure 6.

Figure 6: Instrumentation of defect 1.2.3

In addition, black ink was injected on the gouge to mark the existing micro-cracks before the fatigue test to size the depth of these micro-cracks by fractographic investigation after fatigue failure. The pressure was cycled between 45 bar and 85 bar until failure around 4300 cycles by leak (Figure 7).

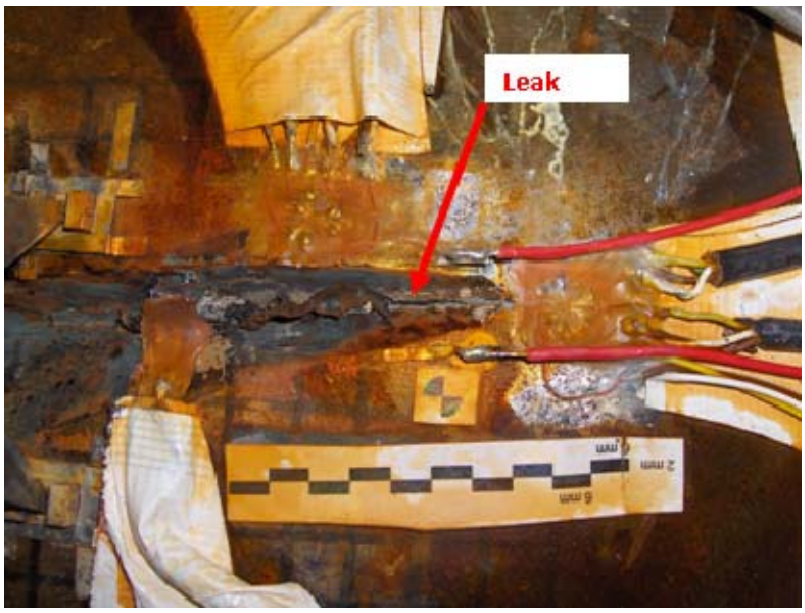


Figure 7: Fatigue failure by leak

Figures 8 and 9 show the clip gauge opening and principal strains from rosette R1 versus the number of cycles for the minimal pressure (45 bar) and maximal pressure (85 bar). From these graphs, the failure occurrence could be around 4300 cycles. Other results from potential drop and other gauges, not shown in this report, confirm this interpretation. The principal strains from rosette 1 in Figure 9 are oriented about following the pipe axis, R1-1 and R1-2 in the axial

direction and R2-1 and R2-2 in the hoop direction. The principal strains in the hoop direction are in tensile, increasing with the cycle numbers, whereas the principal strains in the axial direction are stable around 0.

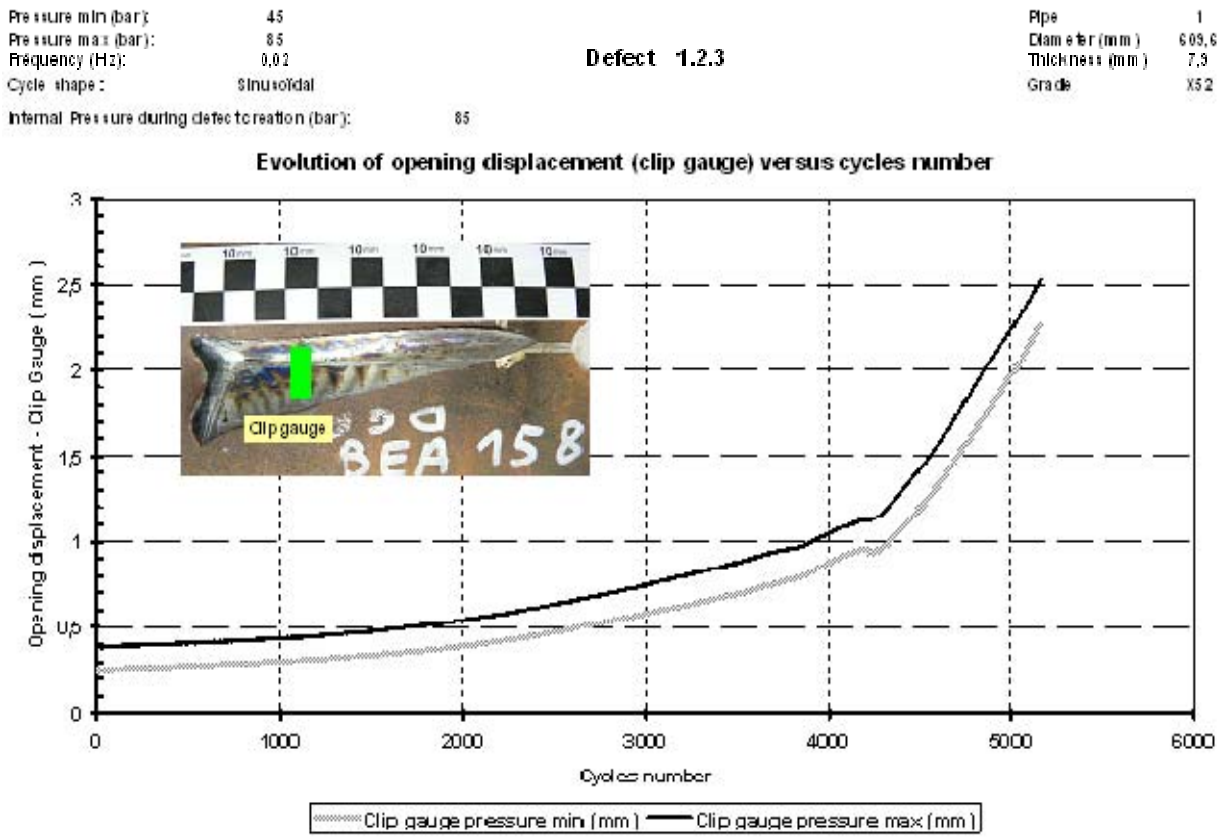


Figure 8: Clip gauge opening displacement versus number of cycles

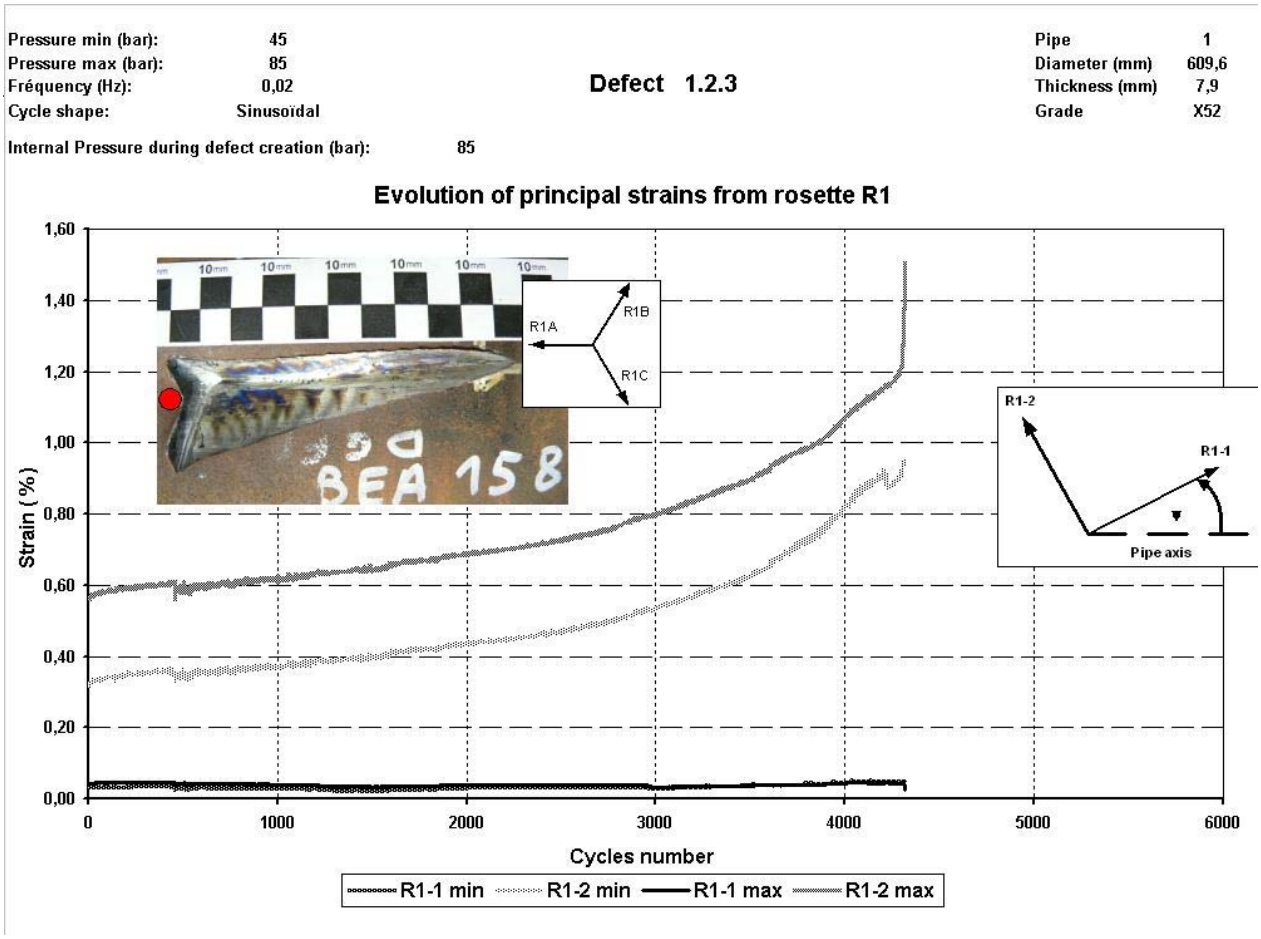


Figure 9: Principal strains versus number of cycles from rosette R1.

- ***Task 5: Testing dents with gouges: Fractographic Fatigue Failure Investigation of defect 1.1.3***

The 10 samples of defect 1.1.3 were broken in liquid nitrogen to observe the failure surface (Figure 10).

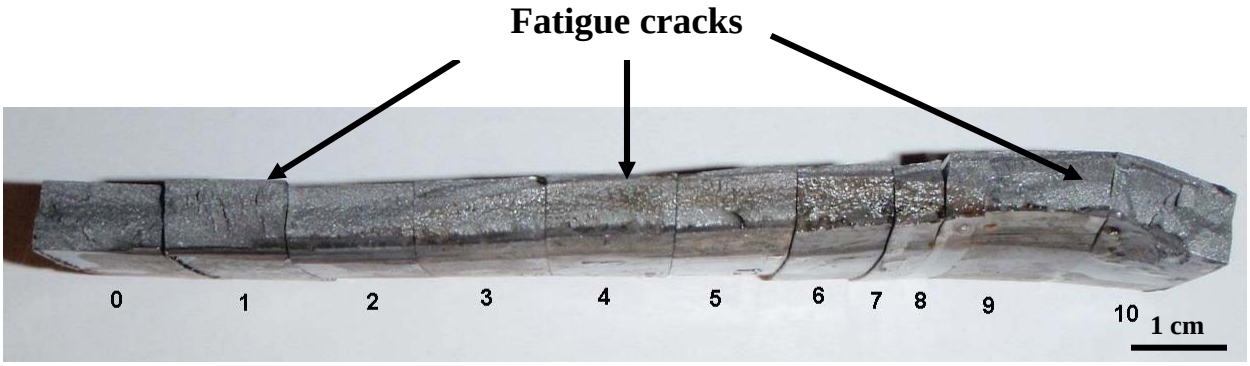


Figure 10: Fatigue failure surface by leak

The macroscopic observation of the failure surface above shows several fatigue cracks. On the samples 4 and 5, the fatigue crack appears to be fully through the wall thickness. In consequence the sample 4 was chosen for SEM examination (Figure 11).

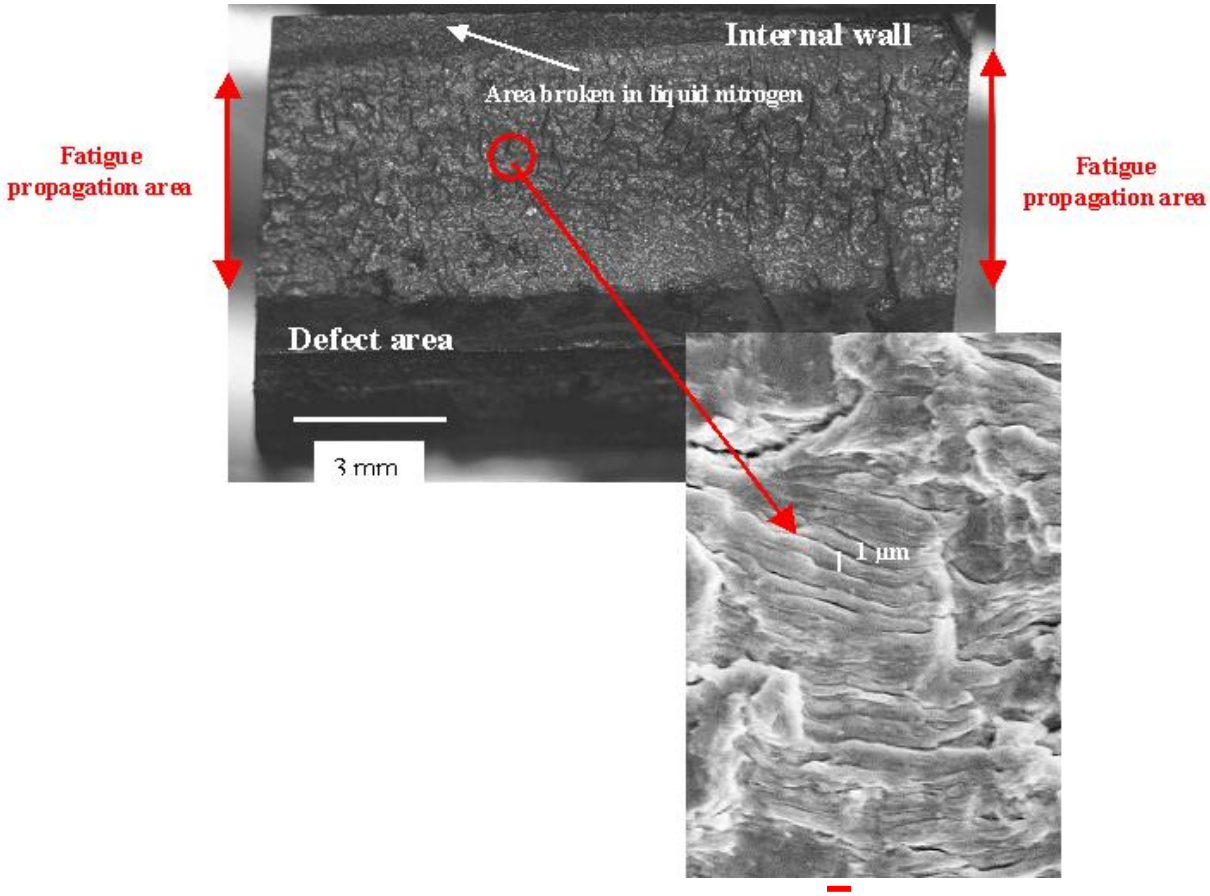


Figure 11: SEM Investigation and fatigue striations at about half-thickness

Figure 11 shows fatigue striations at wall half-thickness with a width around 1µm. With a pressure swing range between 45 bar and 85 bar, ΔK is in the range of [30 MPa√m, 50 MPa√m] at this location. Using Paris law given by API-579 for ferritic steel (formula F-91 Appendix F), the crack propagation speed is calculated with a result in the range of [1 µm/cycle, 4 µm/cycle]. One fatigue striation corresponding at one cycle, the observed striations are in agreement with the fatigue crack propagation speed predicted by the API Paris Law.

- ***Task 5: Surface residual stresses of defects 1.1.1b and 1.2.1b***

Residual stresses were determined on internal and external surfaces of defects 1.1.1.b and 1.2.1.b by X-Ray. Residual stresses on the external surface were determined in both directions (hoop and axial). On the internal surface, only residual stresses in the hoop direction were determined. Figures 12 and 13 show the results with the following color code:

- Blue: Axial residual stress on the external surface;
- Red: Hoop residual stress on the external surface;
- Green: Hoop residual stress on the internal surface.

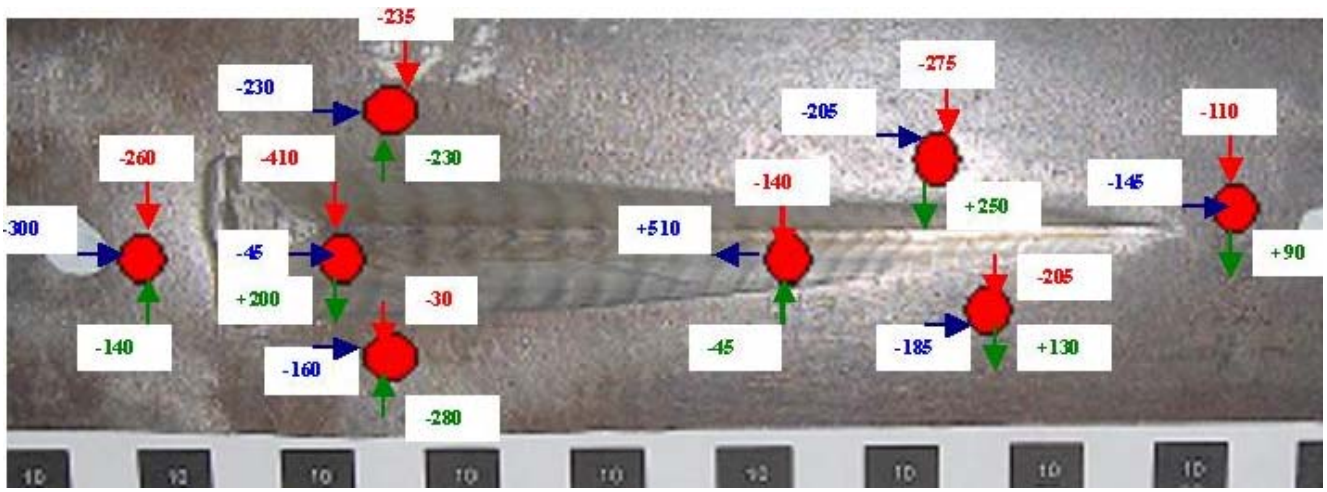


Figure 12: Surface residual stresses for defect 1.1.1b

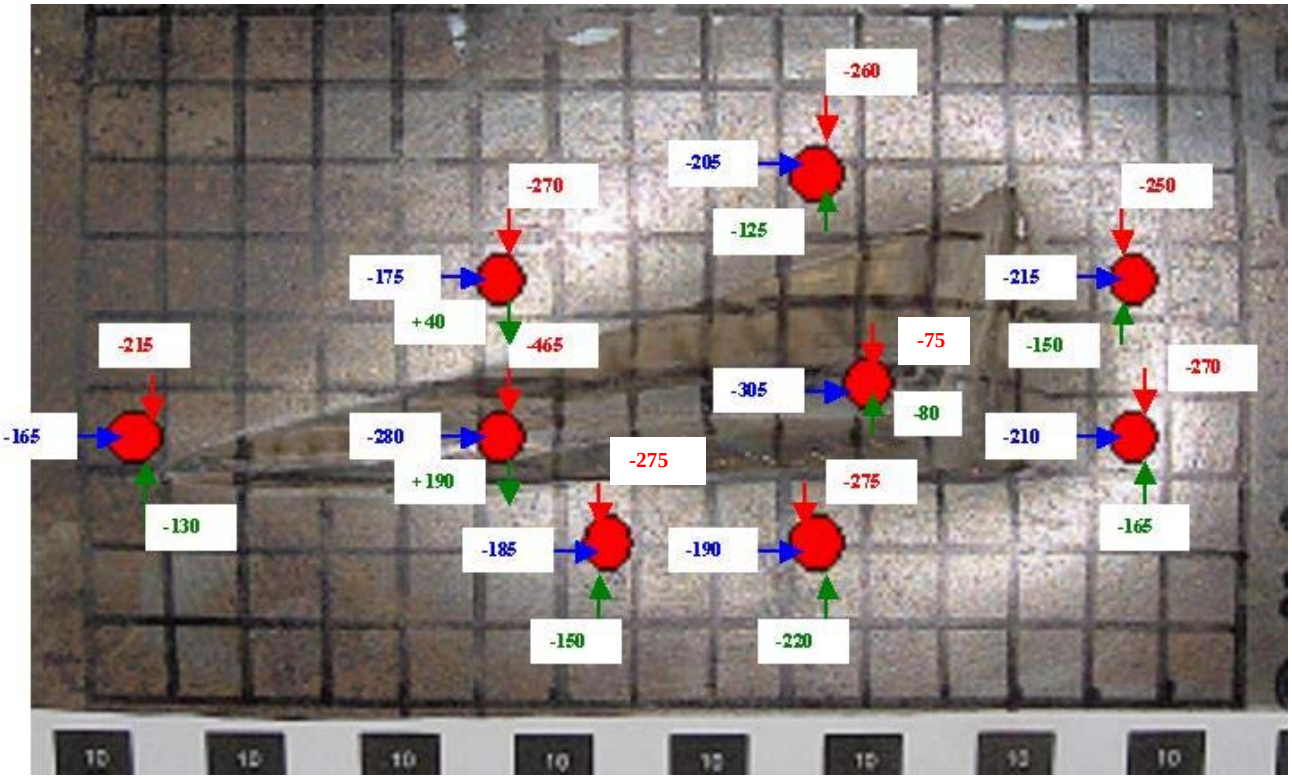


Figure 13: Surface residual stresses for defect 1.2.1b

The residual stresses are very variable from one location to another and can be very high in compression and in tension.

For **defect 1.1.1b**:

- All **hoop residual stresses** are in compression on the **external surface** (red color) with an absolute maximum value of 410 MPa in the gouge at the end of the aggression;

- All **axial residual stresses** are also in compression on **external surface** (blue color), except at the first third of the gouge with a high tensile value of 510 MPa in this location;
- **Hoop residual stresses** on **internal surface** (green color) are in compression at the edges of the gouge at its end, whereas they are in tension at the beginning of the gouge with a maximum value of 250 MPa. In the gouge, a tensile value of 200 MPa is found at the end of the gouge.

For defect 1.2.1b :

- As the previous defect, all **hoop residual stresses** are in compression on the **external surface** (red color) with an absolute maximum value of 465 MPa in the gouge;
- All **axial residual stresses** on **internal surface** (blue color) are in compression with an absolute maximum value of 305 MPa in the gouge;
- **Hoop residual stresses** on **internal surface** (green color) are in compression at the edges of the gouge and one significantly in tension in the gouge (190 MPa).

Residual stresses are also determined in one location in the body pipe, far from the defect and the values are not significant (maximum –100MPa in axial direction on the external surface and 0+/-10 in other cases.

Main Conclusions:

Task 2: Material Characterization

Pre-strain effect on toughness was achieved for Pipe 1. Pre-strain levels in the range of [5%, 10%] affect the toughness J-Curve by about 30%. But this remaining toughness is still very high and should not significantly affect the defect behavior.

Task 5: Fatigue test of defect 1.2.3

The defect 1.2.3 failed by leak around 4300 cycles with a pressure swing range between 45 bar and 85 bar.

Task 5: Fractographic Fatigue Failure Investigation of defect 1.1.3

Samples of the dent and gouge were broken after failure in liquid nitrogen to observe the failure surface. Several fatigue cracks propagated, and one went through the thickness. The SEM investigation showed fatigue striations with an order of width around 1 µm for each striation. This size is in agreement with the size given by the Paris law provided by API 579.

Task 5: Surface residual stresses of defects 1.1.1b and 1.2.1b

Residual stresses were determined on internal and external surfaces of defects 1.1.1b and 1.2.1b. The values are very variable from one location to another and very high values are found in compression and in tension.

Business Status

The project remains well coordinated with the pipeline industry through the PRCI partnership on the project. Please reference Attachment 1 for a summary of details of the resource status of this

Agreement. This attachment includes a quarterly accounting (broken out by Project milestones) of budgeted, current and cumulative expenditures, including cost share amounts. The attachment also explains any major deviations and discusses the adjustment actions proposed.

Schedule & Payable Milestones

Task 2 is slightly behind schedule due to identifying pipe and collecting cost/schedule data for the vintage pipe. Task 3 is behind due to capturing data as it becomes available from sources. Neither task will delay the overall schedule of the project.

Task No.	Task	Status	Scheduled Completion Date	Payable Milestone (Item No)
1	Project Kick Off Meeting and Subcontracting	100% Complete	8/31/2008	
2	Purchase & Characterize Pipe Material	80% Complete	11/30/2008	
3	Literature Review – effect of pre-strain and dent-gouge defect from field feed-back	70% Complete	11/30/2008	
4	Testing of Dents on Welds and Corrosion Features	65% Complete	11/30/2009	16
5	Testing of Dents with Gouges	45 % Complete	5/31/2010	17
6	Demonstration of Mech. Damage Model Performance	0% Complete	5/31/2010	
7	Industry Workshop	0% Complete	5/31/2010	
8	Project Management and Reporting	On-Going	5/31/2010	19

Issues, Problems or Challenges

- To improve the similarity between the created defects of the same type, the aggression tooth has to be examined after the impact test and reshaped to get as close as possible to the same geometry as initially before launching the following test to create a similar defect.
- For the last type of defects in Pipes 1 and 2 (i.e, defect 3), to achieve another extreme defect geometry, the goal is to create a deeper dent and a shallower gouge, via a slower impact. This new type of defect will require some trial and error to achieve the most adequate defect, i.e. to define the parameters and process for the creation.
- The residual stresses in defects called x.x.1 are determined on the same vessel for a given material. This process avoids to waste material using the same vessel for different x.y.1 defects. The consequence is that the residual stress determination and the metallurgical characterization of these already created defects will be performed at the end of the defect creation process for a given material (Pipe 1, Pipe 2, or Pipe 3).

Plans for Future Activity

Planned activities for the project are presented below.

Task 2: Purchase & Characterize Pipe Material

Team is preparing a summary plan outlining the steel procurement justification and cost analysis. Results on pre-strain effect on toughness of pipe 2 material will be compiled.

Task 3: Literature Review

A report summarizing the findings of the literature review of the cyclic fatigue dent assessment techniques will be completed and delivered in the next quarter.

Any new information on pre-strain effect on toughness and on realistic defects from field feedback will be captured as it becomes available from other sources, like conferences, workshops and results of other PRCI projects.

Task 4: Testing of Dents on Welds and Corrosion Features

Full scale testing of dents on welds is ongoing with a scheduled completion date of 08/30/2009. A detailed test matrix summarizing the details of the dents on corrosion features will be completed and provided for review in the next quarter.

Task 5: Testing of Dents with Gouges

Launch fatigue test for defect 2.1.3. Launch the creation of defects 1.3.1 and 2.2.1. During the PRCI technical exchange meetings, the MD4-1 project team decided for these defects a deep dent and shallow gouge. Metallurgical investigation of defect 1.2.3 will be performed.

Attachment 1: Business Status Section

DOT Portion						Cost Share Portion					
Item No.	Task No. (per proposal)	Quarter No.	Budgeted Amount	Current Amount	Cumulative Amount	Item No.	Task No. (per proposal)	Quarter No.	Budgeted Amount	Current Amount	Cumulative Amount
1	1	1	$9,335	$9,335	$9,335	1	1	1	$831	$831	$831
2	2	1	$19,567	$19,567	$19,567	2	2	1	$51,654	$51,654	$51,654
3	3	1	$8,111	$8,111	$8,111	3	3	1	$4,803	$4,803	$4,803
4	4	1	$32,606	$32,606	$32,606	4	4	1	$307,539	$307,539	$307,539
5	5	1	$0	$0	$0	5	5	1	$47,065	$47,065	$47,065
NR	6	1	$0	$0	$0	NR	6	1	$0	$0	$0
NR	7	1	$0	$0	$0	NR	7	1	$0	$0	$0
6	8	1	$7,747	$7,747	$7,747	6	8	1	$4,242	$4,242	$4,242
		1	**$77,366**	**$77,366**	**$77,366**			**1**	**$416,134**	**$416,134**	**$416,134**
NR	1	2	$0	$0	$9,335	NR	1	2	$0	$0	$831
7	2	2	$15,107	$0	$19,567	7	2	2	$44,453	$0	$51,654
8	3	2	$3,438	$0	$8,111	8	3	2	$3,866	$0	$4,803
9	4	2	$31,325	$31,325	$63,931	9	4	2	$58,690	$58,690	$366,228
10	5	2	$34,559	$34,559	$34,559	10	5	2	$37,426	$37,426	$84,491
NR	6	2	$0	$0	$0	NR	6	2	$0	$0	$0
NR	7	2	$0	$0	$0	NR	7	2	$0	$0	$0
11	8	2	$7,747	$7,747	$15,495	11	8	2	$4,242	$4,242	$8,483
		2	**$92,177**	**$73,632**	**$150,998**			**2**	**$148,677**	**$100,357**	**$516,491**
NR	1	3	$0	$0	$9,335	NR	1	3	$0	$0	$831
NR	2	3	$0	$0	$19,567	NR	2	3	$0	$0	$51,654
NR	3	3	$0	$0	$8,111	NR	3	3	$0	$0	$4,803
12	4	3	$31,144	$31,144	$95,075	12	4	3	$58,351	$58,351	$424,579
13	5	3	$33,270	$33,270	$67,829	13	5	3	$26,439	$26,439	$110,930
14	6	3	$2,952	$0	$0	14	6	3	$5,530	$0	$0
NR	7	3	$0	$0	$0	NR	7	3	$0	$0	$0
15	8	3	$7,747	$7,747	$23,242	15	8	3	$4,242	$4,242	$12,725
		3	**$75,113**	**$72,162**	**$223,159**			**3**	**$94,561**	**$89,031**	**$605,522**
NR	1	4	$0	$0	$9,335	NR	1	4	$0	$0	$831
NR	2	4	$0	$0	$19,567	NR	2	4	$0	$0	$51,654
NR	3	4	$0	$0	$8,111	NR	3	4	$0	$0	$4,803
16	4	4	$31,144	$31,144	$126,219	16	4	4	$58,351	$58,351	$482,930
17	5	4	$35,819	$35,819	$103,648	17	5	4	$46,463	$46,463	$157,393
18	6	4	$2,882		$0	18	6	4	$5,400	$0	$0
NR	7	4	$0	$0	$0	NR	7	4	$0	$0	$0
19	8	4	$7,747	$7,747	$30,990	19	8	4	$4,242	$4,242	$16,966
		4	**$77,593**	**$74,711**	**$297,870**			**4**	**$114,455**	**$109,055**	**$714,577**