QUARTERLY REPORT
Project WP#339: Structural Significance of Mechanical Damage

Date of Report February 28, 2011

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Office of Pipeline Safety

Project Title Project WP#339: Structural Significance of Mechanical Damage

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For Period Ending: February 28, 2011

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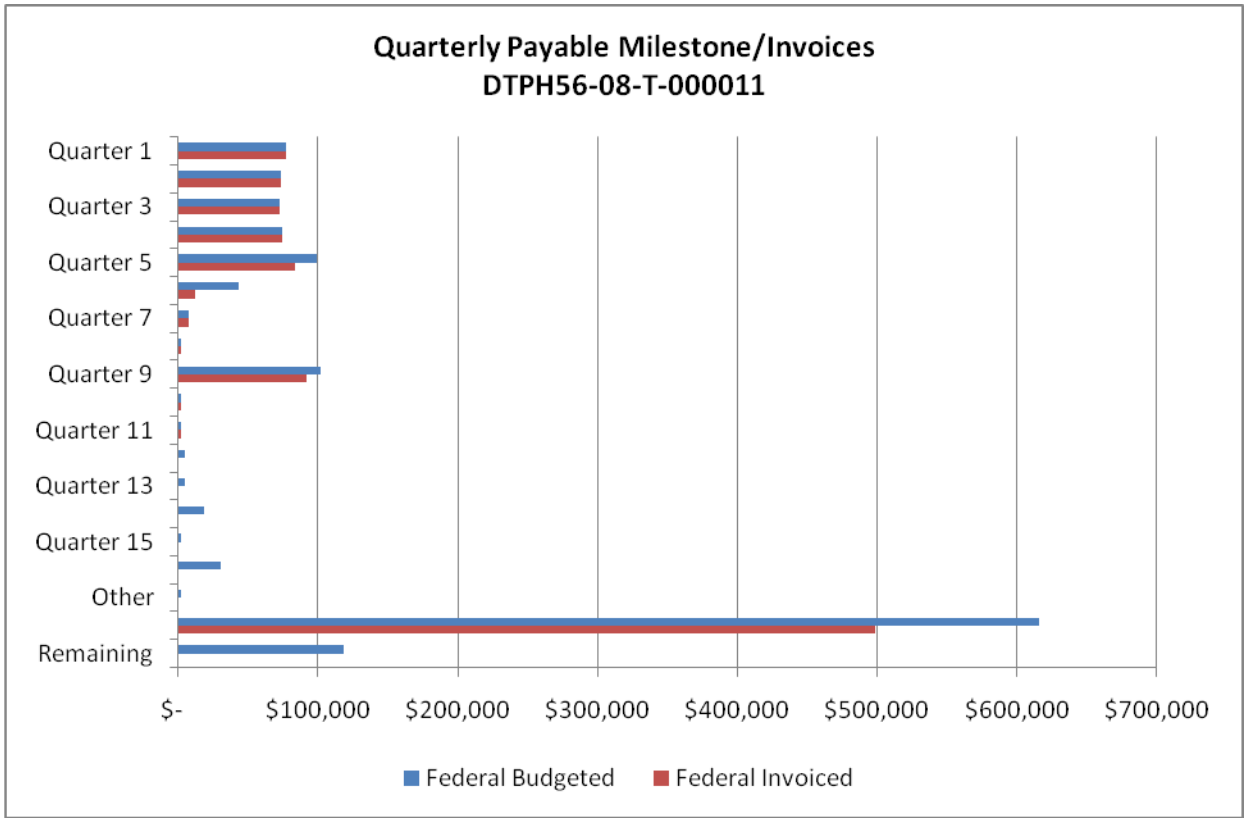
Funds and Work Completed During this Quarterly Period



Technical Status

Technical activities undertaken through the Eleventh Quarter focused on the following tasks:

- Task 2—Purchase & Characterize Pipe Material
- Task 3—Literature Review
- Task 4—Testing of Dents on Welds and Corrosion Features
- Task 5—Testing of Dents with Gouges
- Task 8 – Project Management and Reporting

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

The technical group for this program has maintained close communication with other related research projects being conducted by PRCI and DOT to ensure program coordination. The team has forwarded any issues of concern to PRCI and DOT for their consideration.

Task 2: Purchase & Characterize Pipe Material

There are currently four different pipe steels in this program:

- Pipe 1 and 2 are modern IPSCO pipes manufactured between 2005 and 2006

- Pipe 3 is older steel to represent the majority of the pipelines in-service. It was initially intended to provide a manufactured pipe that replicates vintage pipe properties for Pipe 3. Due to challenges identified with this initial approach, the project is now using vintage pipe from former in-service pipelines provided by PRCI member companies. This has resulted in use of several different pipes, one vintage material for the full-scale testing program for dents, named Pipe 3, and

- A separate vintage material for creating and testing dent and gouge defects, named Pipe 4. (There are actually several candidates for selection, named 4 a, 4 b and 4 c.)

BMT has completed the detailed material characterization work on the vintage Pipe 3 material (X52, 18 in. outside diameter) which the team is using in the extended full scale test matrix of plain dents and dents interacting with welds and corrosion metal loss. Their material characterization work included preliminary tests on five randomly selected pipes from Pipe 3 (which has been removed from the ground) and the complete detailed characterization on at least one pipe.

BMT's detailed material characterization work included the following:

- Chemical Analysis on five pipes
- Optical Microscopy on five pipes
- Hardness (mid thickness and surface) on five pipes
- Upper shelf CVN toughness on five randomly selected pipes and CVN transition curves on three pipes
- Tensile tests (flat longitudinal, transverse flattened strap, round longitudinal and round transverse) on five pipes
- Cyclic stress strain curve on one pipe
- Quantitative metallography (ferrite grain size, pearlite volume fraction and inclusion volume fraction) on two pipes
- CTOD (base metal) on three pipes
- Strain life fatigue tests on one pipe

A report detailing the characterization efforts and results is being finalized and will be circulated within the next quarter.

BMT also performed preliminary characterization on vintage Pipe 4a (24 in. diameter and 0.25 in. nominal thickness), see Table 1 below, to complement the dent + gouge test program. The results reflect relatively good characteristics for a vintage pipe, especially its Charpy toughness. SES characterized another vintage pipe named 4 b, with the hope of a lower Charpy V toughness and a thicker wall. A third vintage pipe 4c (Year 1967) from GDF SUEZ was also recently proposed for the study. Charpy values are not yet available, but underway. Once all characterization results are available for all three pipes (4a, b and c), the project team will decide on the pipe they will use to represent vintage pipe materials in the dent and gouge tests.

Table 1: Characteristics of Vintage Pipes 4 a, b and c - basic characterization for selection before Dent and Gouge tests

	Diameter thickness	Tensile Properties Basic characterization	Charpy - Basic characterization
Pipe 4 a based in U.S.	24″ 0.25″	**Transverse (flattened)** **YS=400MPa-413MPa** **UTS =538MPa-542MPa** **Longitudinal** **YS=370MPa-375MPa** **UTS =528MPa-568MPa**	45 J/cm²-60 J/cm² @ 20°C
Pipe 4 b based in U.S.	24″ 0.29″	**Transverse (flattened)** **YS=404MPa-482MPa** **UTS =552MPa-579MPa** **Longitudinal** **YS=460MPa-485MPa** **UTS =555MPa-580MPa**	37 J/cm²-48 J/cm² @ 20°C
Pipe 4 c based in France	24″ 0.27″min X63 grade (1967)	**Transverse** **YS=469MPa, UTS =610MPa**	Ongoing

Task 3: Literature Review

The literature review regarding cyclic fatigue dent assessment techniques is complete. A report summarizing the findings and demonstrating the performance of the identified assessment techniques will be available following the completion of the testing.

Task 4: Testing of Dents on Welds and Corrosion Features

BMT has completed the fatigue testing of the first eight Pipe 3 plain dent specimens. A summary of the experimental results is presented in Table 22 below.

Table 2: Summary of Initial Eight Pipe 3 Plain Dent Experimental Results

Specimen #	Nominal Indenter Diameter (in)	Indenter Travel (%)	Dent Restraint	Indentation Pressure	Initial Pressure Cycle (%SMYS)	Cyclic Pressure Range (%SMYS)	Weld Seam/Indenter Location	Cycles to Failure
41	2	5	R	0%	100%	10%-80%	NA	69099
42	4	10	R	0%	100%	10%-80%	NA	69393
46	12	5	R	0%	100%	10%-80%	NA	125525
48	2	15	U	0%	100%	10%-80%	NA	23482
52	4	15	U	0%	80%	10%-80%	NA	9226
54	12	15	U	0%	100%	10%-80%	NA	47702
56	4	20	U	0%	100%	10%-80%	NA	15473
57	12	20	U	0%	80%	10%-80%	NA	14091

Figure 1 through Figure 3 present the detailed experimental results in terms of the indentation load versus indenter displacement, the initial unrestrained dents shapes and the dent shapes after the second pressure hold.

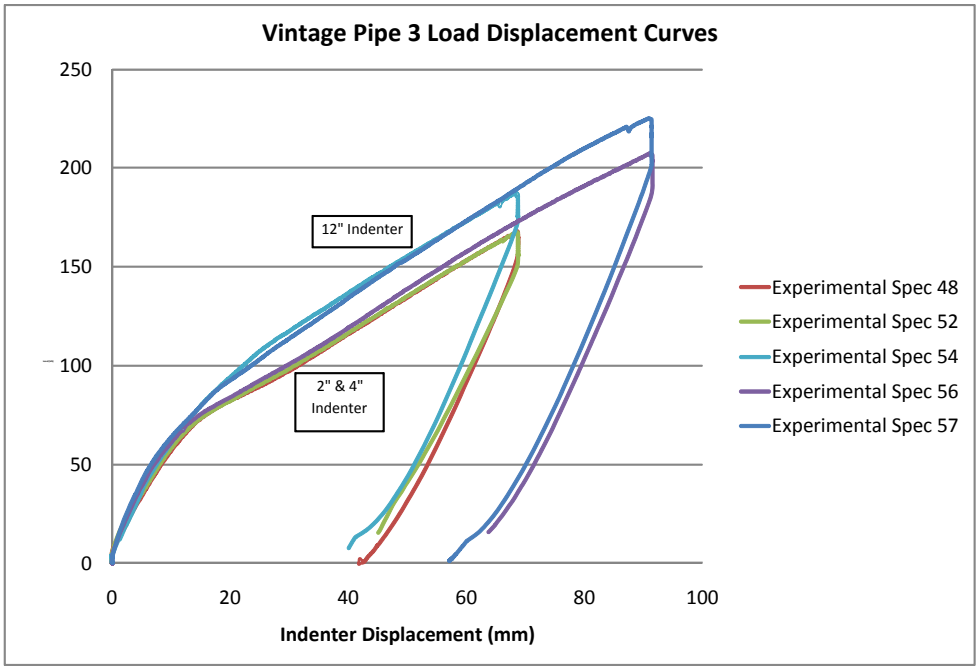


Figure 1: Comparison of Pipe 3 Plain Dent Indentation Load vs. Indenter Displacement

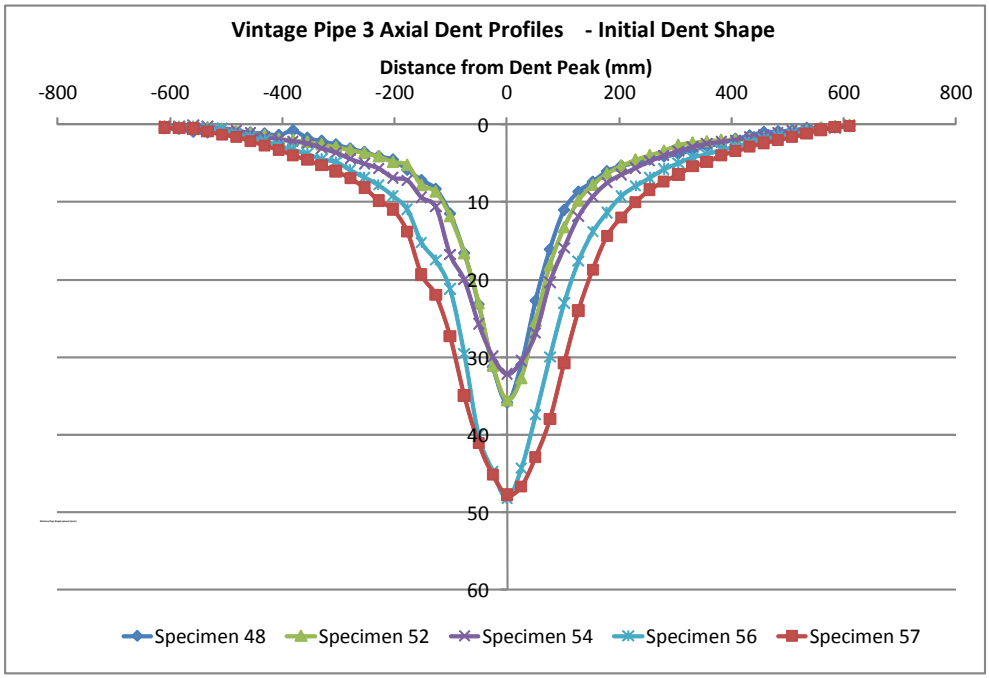


Figure 2: Comparison of Pipe 3 Plain Dent– Unrestrained Dents – Initial Dent Shape

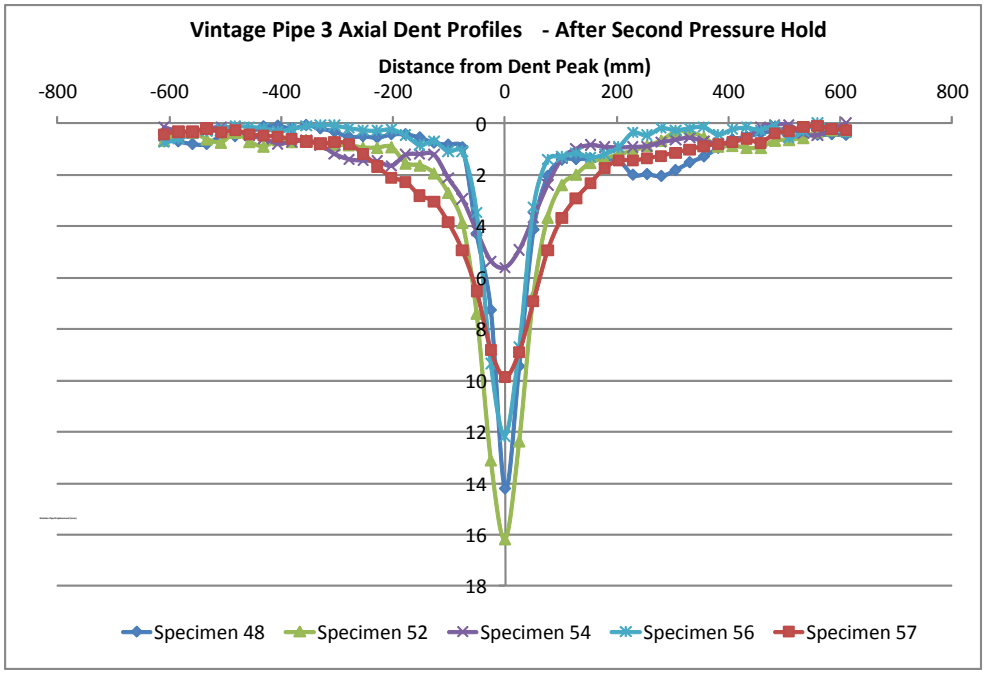


Figure 3: Comparison of Pipe 3 Plain Dent– Unrestrained Dents –Dent Shape After Second Pressure Hold

The team presented the results of the full scale tests including the recently completed plain dent tests on vintage pipe (Pipe 3) at the PRCI Research Exchange meeting held in Atlanta, Georgia, on Feb1-3 2011.

Task 5: Testing of Dents with Gouges

GDF SUEZ is in charge of the creation, characterization, burst test, and fatigue test of realistic combined defects, i.e., "dents with gouges", and their program is 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 is noted by 1, 2, or 3 in this program;

- 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. This program is considering a maximum of three different kinds of defects per pipe material, and therefore, the value of Y can range from 1 to 3; two extreme aggression conditions are considered in this study: highly dynamic and slower aggression. The former corresponds to defect Types 1 and 2 for Pipe 1 (two different excavator teeth used) and Type 1 for Pipe 2, while the latter corresponds to Type 3 for Pipe 1 and Type 2 for Pipe 2.

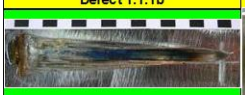
- X.Y.**Z.**—**Z** is the **number of defect in the defined type of defect**. There are three similar defects per type of defect. The number 1 is for a detailed geometrical, mechanical and metallurgical in-depth defect characterization after its creation. Number 2 is a similar defect for the burst test 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.

This report presents the metallurgical investigation of defect 2.2.3;

Table 33 below summarizes the progress of the task on "Dent and Gouge" defects for the MD4-1 part of the program. The background color in the table represents:

- White: Defects not yet created
- Yellow: Defects already created but not yet characterized/investigated or submitted to either burst or fatigue tests
- Green: Defects created and tests completed

Table 3: Status of "Dent and Gouge" defects for the MD4-1part of the program

MD 4-1					DOT	
Pipe 1 (current steel X52)			Pipe 2 (current steel X70)		Pipe 4 (older	
Type 1	Type 2	Type 3	Type 1 or 2	Type 2 or 3	Type 1 or 2	Type 2 or 3
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 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 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

Task 5: Metallurgical investigation of defect 2.2.3

GDF SUEZ cut this defect created by slow dynamic aggression into several samples after it failed under fatigue in order to investigate the microstructure, presence of cracks and to estimate local strains (Figure 4 and Figure 5). Due to its length of more than 350 mm, GDF SUEZ cut it into 24 samples numbered 0 to 23.

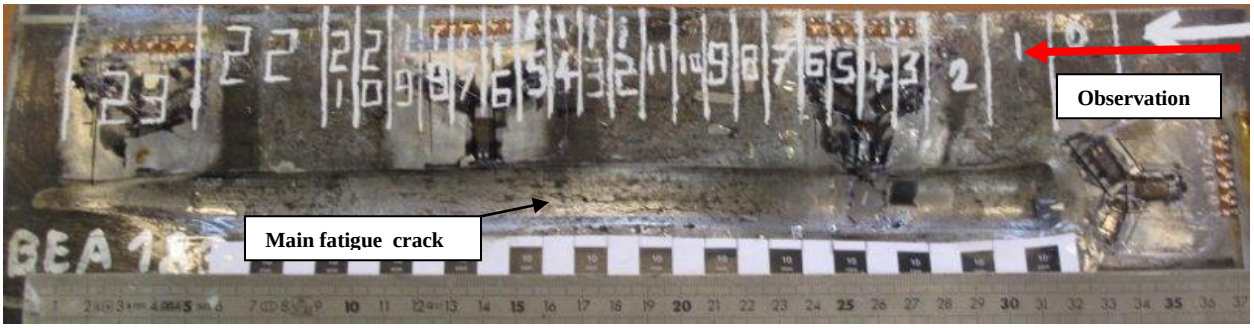


Figure 4: Defect 2.2.3 before cutting, with samples reference # and observation direction

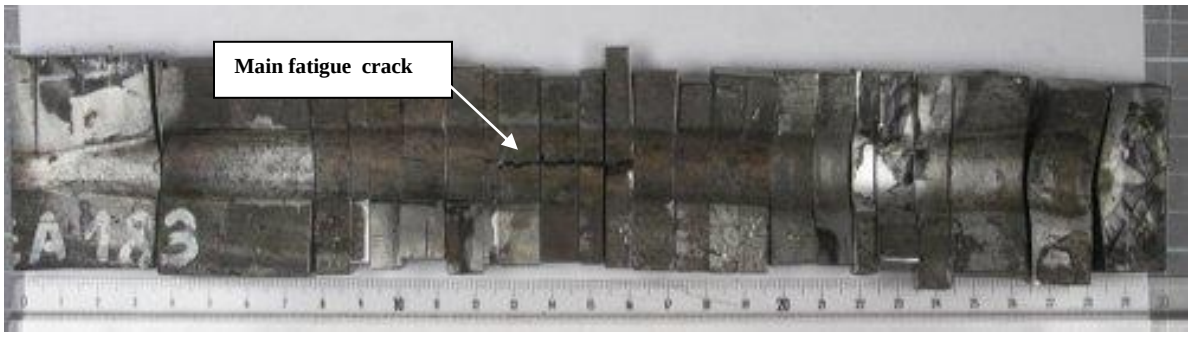


Figure 5: Defect 2.2.3 after cutting of samples into 24 samples due to its length.

Figure 6-8 provide macroscopic photos of samples 9, 14 and 17.

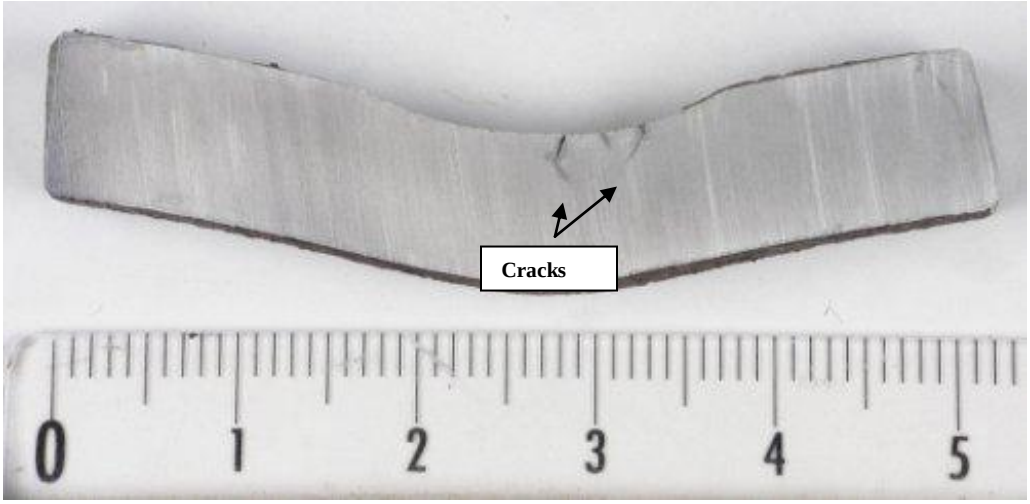


Figure 6: Defect 2.2.3 - sample 9 with two significant cracks (20-25%) and a third smaller one.

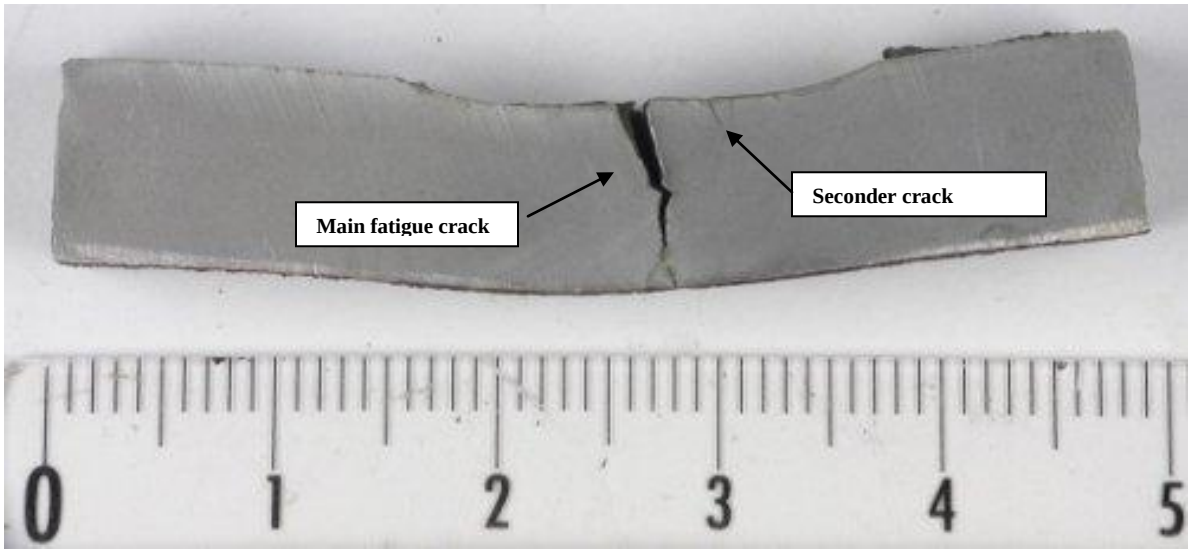


Figure 7: Defect 2.2.3 - sample 14 showing the main fatigue crack and a secondary crack.

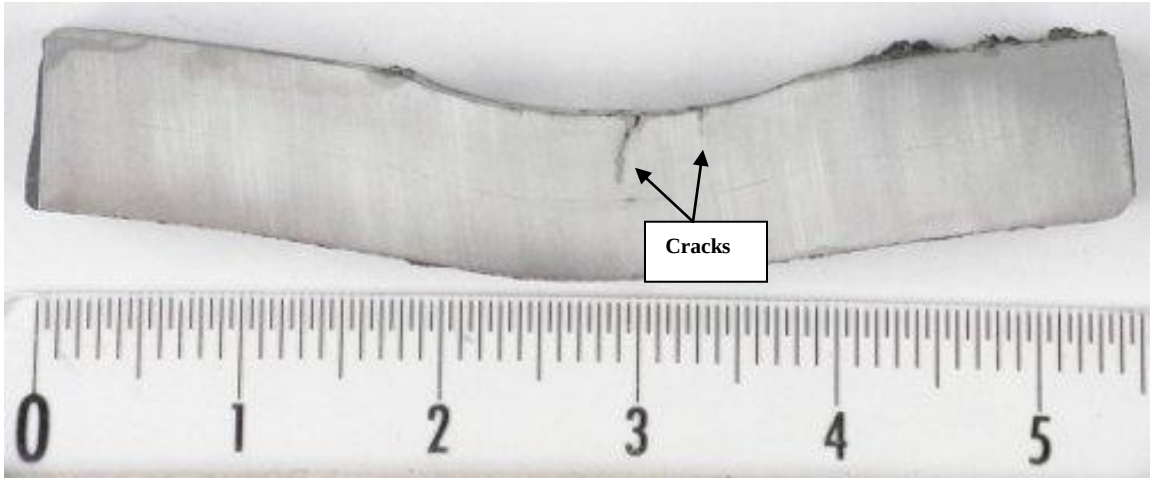


Figure 8: Defect 2.2.3 - sample 17 with the end of the main fatigue crack and a secondary crack.

GDF SUEZ measured the crack depth on 169 cracks from the cut samples 9 to 18 and plotted in a histogram shown in Figure 9.

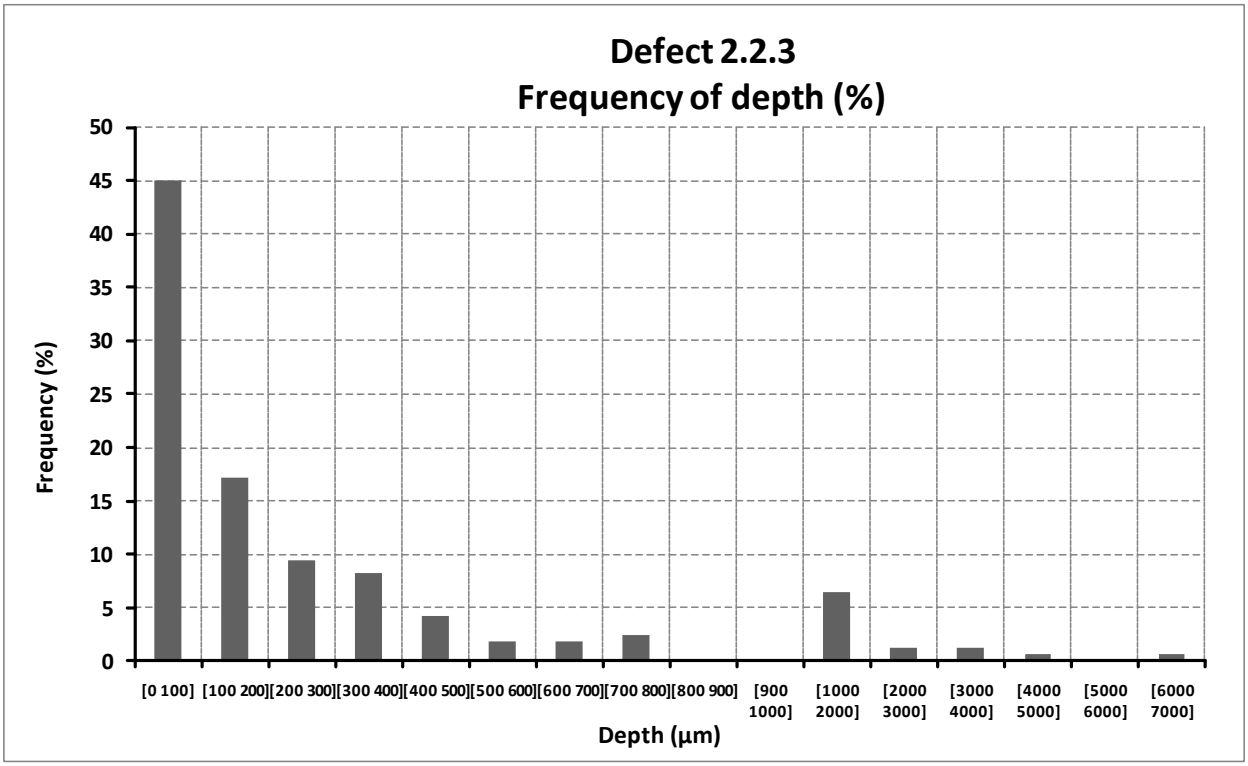


Figure 9: Distribution of crack depths measured on 169 cracks from samples 9 to 18.

Almost half (45%) of cracks are less deep than 100 µm, and two thirds (67%) are less than 200 µm deep. While more than 10% of the cracks are deeper than 1 mm. The team believes the largest cracks are most likely propagating during the fatigue test. However, for the majority of very shallow cracks (i.e., less than 100-200 µm), the team is trying to determine if their size is due to crack initiation upon defect creation, re-rounding, or during the fatigue test. The researchers found no indication of cracking using magnetic particle inspection (MPI) after defect

creation, so they need to assess the detection limit of this qualitative technique. The team did not observe a hard layer at the gouge surface as shown in the microscopic views (Figure 10 and 11) which would have originated from tooth material welded on the surface like they found in the case of highly dynamic aggression.

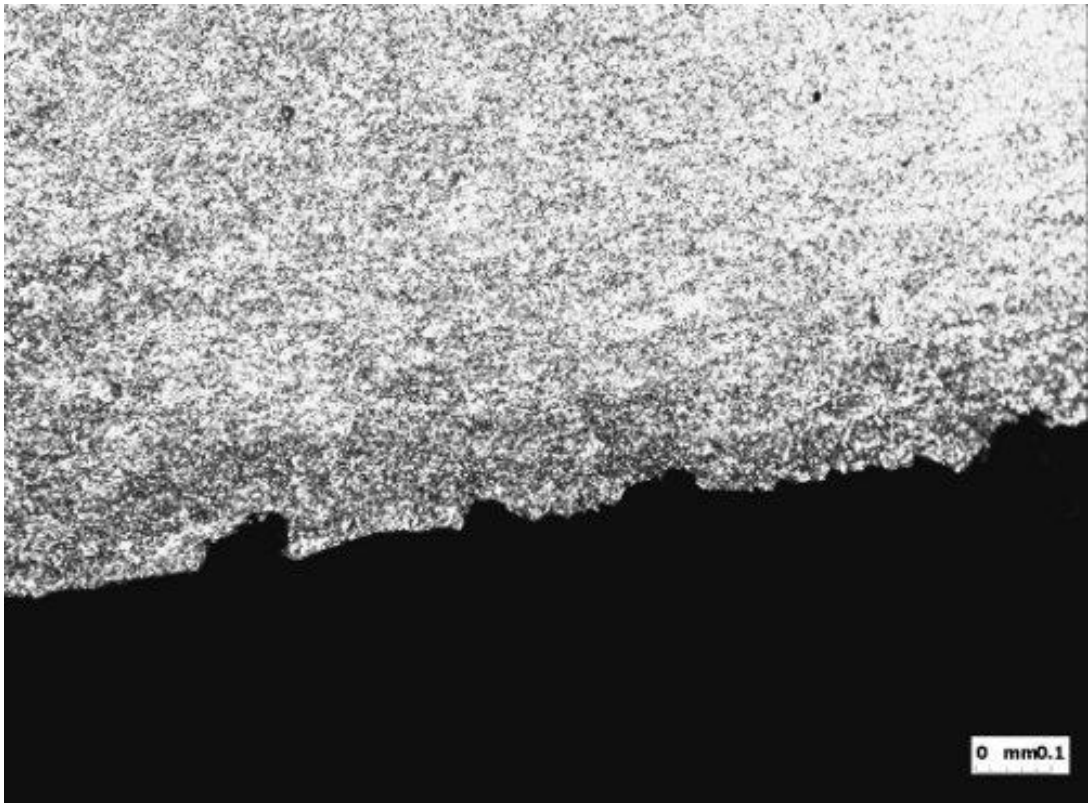


Figure 10: Defect 2.2.3 - Microscopic view close to the gouge surface from sample 17.

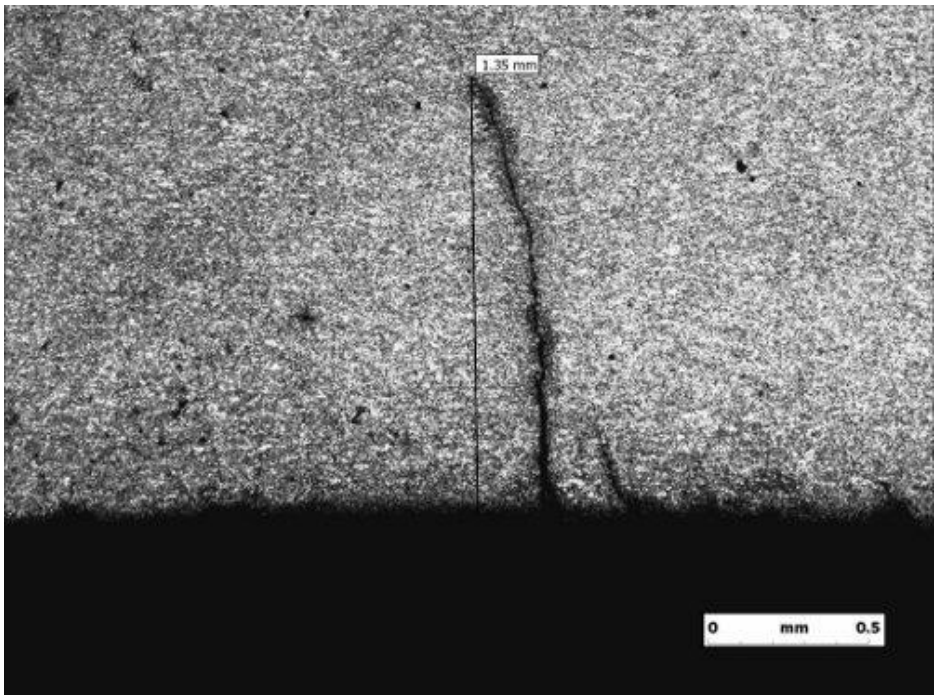


Figure 11: Defect 2.2.3 - Microscopic view close to the gouge surface from sample 13, with a crack of 1.35 mm depth and a secondary shallow crack.

Several cracks propagated from geometrical imperfections at the gouge surface (Figure 12) or initiated by microscopic material defects (possible inclusions) in subsurface (Figure 13).

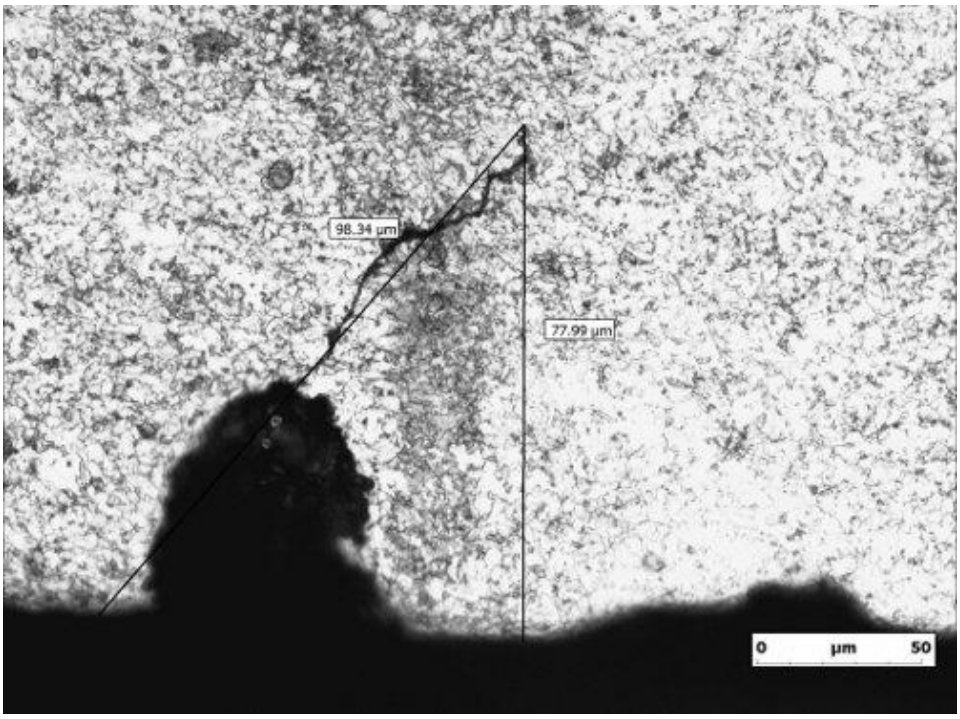


Figure 12: Defect 2.2.3 - Geometrical imperfection at the gouge surface where a crack (78 – 98 µm) originates - sample 15

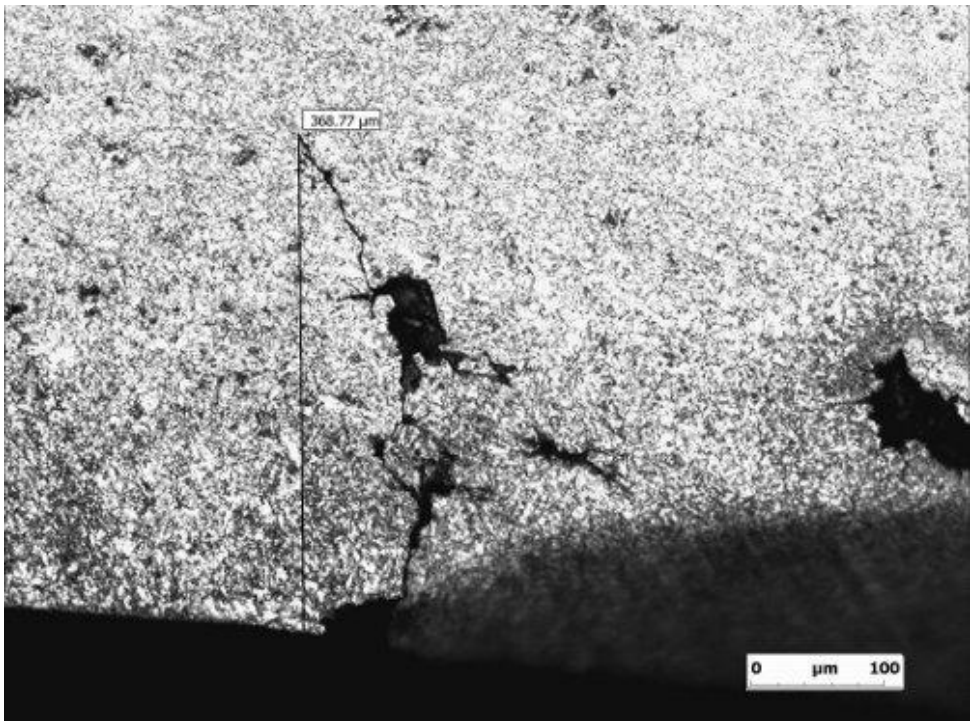


Figure 13: Defect 2.2.3 – Microscopic view of material defect (possible inclusion) at gouge subsurface and crack –sample 15

At pipe mid-wall thickness under the dent+gouge feature, the microstructure is stretched with elongated ferritic grains due to significant local deformation (Figure 14).

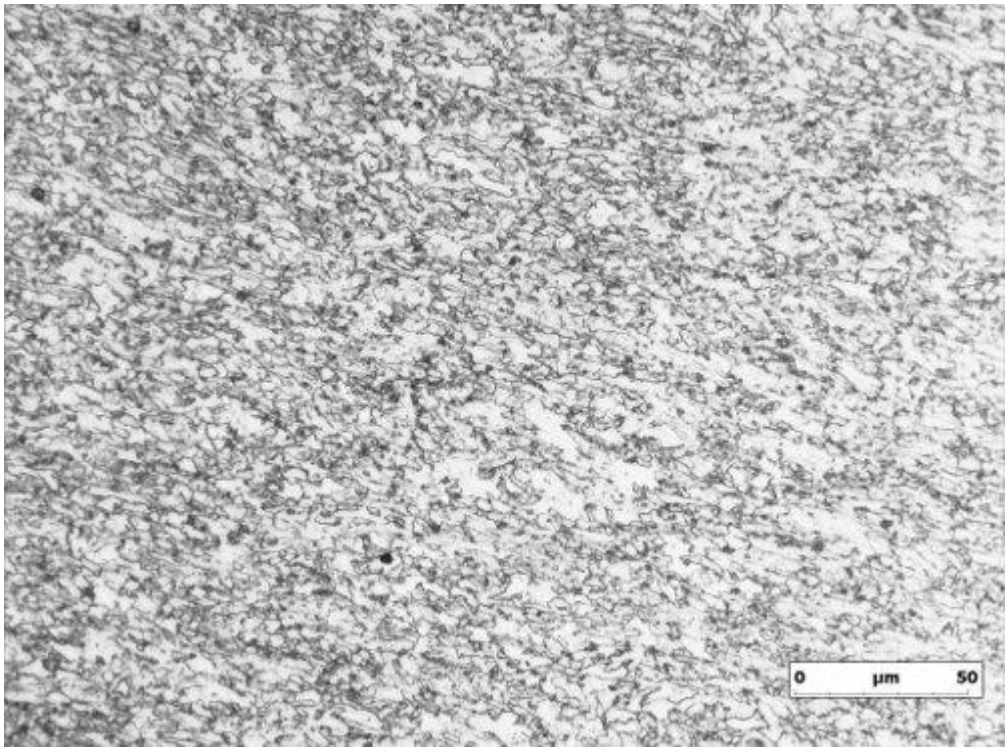


Figure 14: Defect 2.2.3 with stretched ferritic grains at mid-wall under dent – sample 14.

GDF SUEZ made several micro-hardness progressions through the thickness from dent surface to internal wall on several cuts at five positions represented by color code in Figure 15:

- Black line: Micro-hardness Progression 1;
- Green line: Micro-hardness Progression 2;
- Red line: Micro-hardness Progression 3;
- Blue line: Micro-hardness Progression 4;
- White line: Micro-hardness Progression 5.

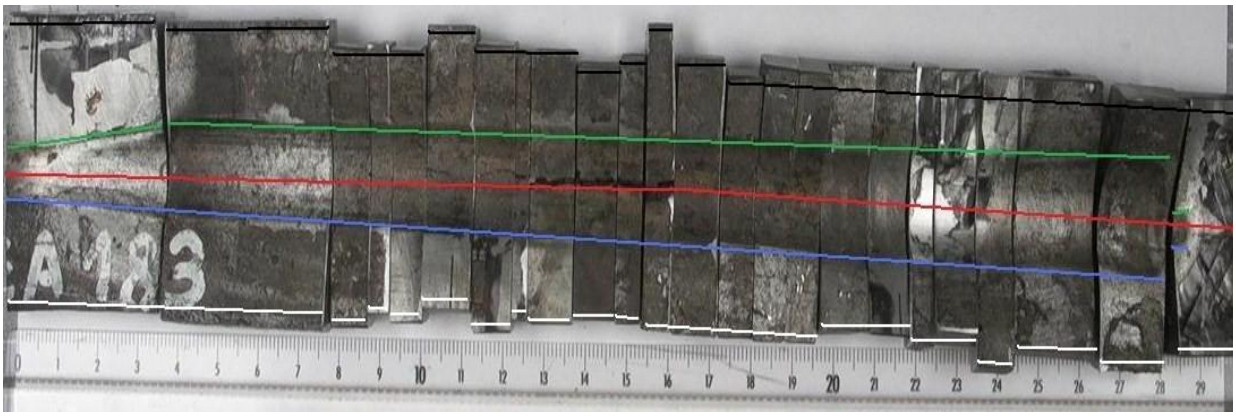


Figure 15: Defect 2.2.3 - Micro-hardness progression positions

Micro-hardness values were converted to strains by the empirical formulation:

$$\boxed{\varepsilon_{\%} = 0.3377 \times HV_{0.5} - 56.786}$$

As an example, Figure 16 shows the local strains deduced form micro-hardness profiles for the five micro-hardness progressions on Sample 14. The researchers estimate local strains of up to 30% under the dent.

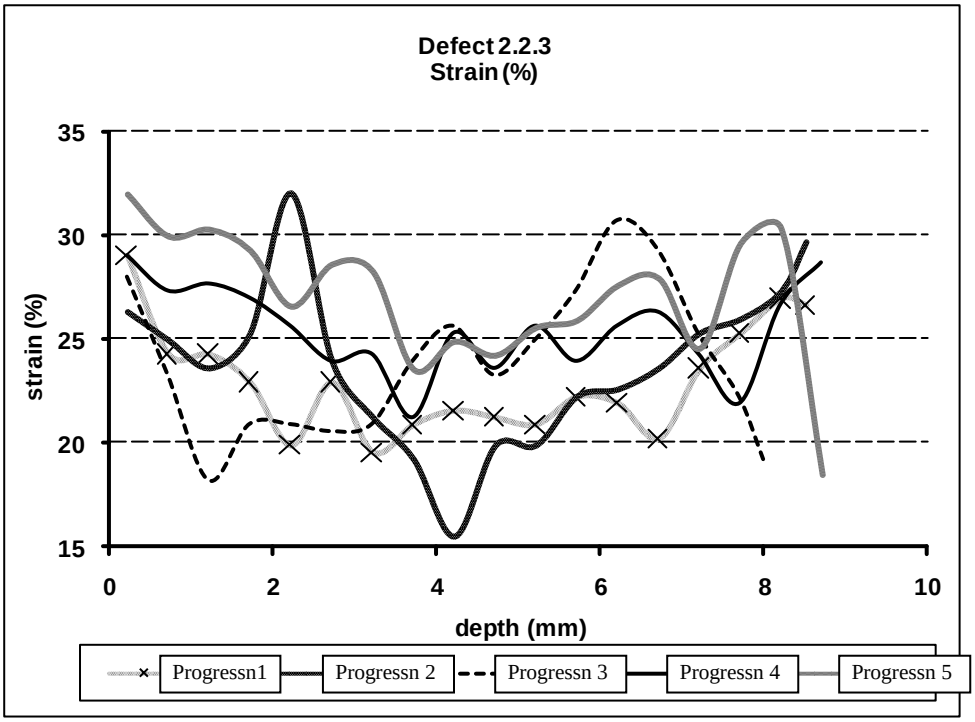


Figure 16: Defect 2.2.3 - Local strains Profile along the thickness under the dent – sample 14.

Technical Results and Conclusions

A summary of the results are:

- Task 2—Material characterization are complete for Pipe 1 and Pipe 2;
- Task 3—The literature review of cyclic fatigue dent assessment techniques is complete;
- Task 4—The testing of dents interacting with girth welds is complete;
- Task 5—The fatigue test on defect 1.3.3 is ongoing and its lifetime has exceeded 18,000 cycles. Additional investigation of the hardened layer showed that this layer could be created from tooth material deposited during aggression.

Technical Issues, Problems or Challenges

As discussed above, the team began preliminary material characterization of the vintage pipe for Pipe 3 in September 2010 and went on with other vintage pipes (i.e., Pipe 4 and other pipe materials to be used for dent+gouge test samples). However, the full characterization will continue through at least March 2011. The team believes that this delay will not affect the overall project schedule, since other testing will continue in parallel during this time. The team is in the process of evaluation options to expedite the characterization process.

Plans for Future Activity

Planned activities for the project are presented below.

Task 2: Purchase & Characterize Pipe Material

The team is characterizing three vintage pipes (Pipe 4a, b, and c) which are potential candidates for the DOT program. GDF SUEZ is providing one pipe and they have to confirm Charpy

values. The team expects the results before the end of March 2011. Then, they will choose between the three vintage pipes and will start the dent + gouge tests on the chosen vintage pipe.

Task 4: Testing of Dents on Welds and Corrosion Features

The full scale test matrix for the next set of Pipe 3 dent fatigue tests will be finalized and circulated to the project team and PRCI member companies for approval and subsequent testing.

Task 5: Testing of Dents with Gouges

GDF SUEZ will continue the destructive characterization of defect 1.1.1b and will send defects 1.2.1b, 2.1.1 and 2.2.1 to Chalk River in Canada for neutron diffraction analysis of residual stresses.

Business Status

The team has prepared a proposal for increasing the test variables for full scale dent tests and will submit it to DOT and PRCI.

Funds Expended

The financial condition of the project is shown in the table below.

		Federal Funding			Cost Share Funding			
Task # per MS	**Task Description**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**% Complete**
1	Project Kick Off Meeting and Subcontracting	$9,335	$0	$9,335	$831	$0	$831	100%
2	Purchase & Characterize Pipe Material	$134,674	$90,000	$109,567	$146,108	$0	$96,108	100%
3	Literature Review	$11,549	$0	$11,549	$8,669	$0	$8,669	100%
4	Testing of Dents on Welds & Corrosion Features	$188,507	$0	$157,363	$599,632	$75,432	$575,018	75%
5	Testing of Dents with Gouges	$150,020	$0	$150,020	$254,404	$31,238	$228,571	65%
6	Demonstration of Mechanical Damage Model Performance	$22,008	$0	$0	$10,930	$0	$0	40%
7	Industry Workshop	$12,030	$0	$0	$4,325	$0	$0	0%
8	Project Management and Reporting	$88,366	$1,834	$58,910	$43,959	$0	$1,692	On-going
	GRAND TOTAL	**$616,490**	**$91,834**	**$496,744**	**$1,068,858**	**$106,670**	**$910,889**	

Schedule

The project is generally on schedule, but as discussed in prior reports, Task 5 was impacted by the decision to add neutron diffraction testing of selected dent + gouge samples to the program. Two defects 1.1.1b and 1.3.1 were returned from the neutron diffraction testing and GDF SUEZ has begun the destructive metallurgical investigation of defect 1.1.1b. They will send three other defects, 1.2.1b, 2.1.1 and 2.2.1 to Canada next month for neutron diffraction to determine residual stresses. The researchers expect that they will return to France in the fall of 2011 for destructive analysis which they will complete by the end of the year. The researchers believe the data generated will be very beneficial for improving the understanding of the dent + gouge defects behavior and for providing further input to improve current mechanical damage remaining strength assessment models.

Task No.	Task	Scheduled Completion Date	Completed Date	% Complete	Status (if delayed)
1	Project Kick Off Meeting and Subcontracting	8/31/2008	8/31/2008	100%	
2	Purchase & Characterize Pipe Material	8/31/2010	02/01/2011	100%	Pipe 1 and 2 complete, work on Vintage Pipe 3 is on-going.
3	Literature Review	11/30/2009	11/30/2009	100%	
4	Testing of Dents on Welds and Corrosion Features	2/28/2012	Ongoing	75%	
5	Testing of Dents with Gouges	2/28/2012	Ongoing	65%	
6	Demonstration of Mechanical Damage Model Performance	11/30/2011	Ongoing	40%	
7	Industry Workshop	5/31/2012	Not Yet Started	0%	
8	Project Management and Reporting	5/31/2012	Ongoing	On-going	

Payable Milestones

Payable milestones for this period are shown in the table below.

		Federal Funding			Cost Share Funding			
Task # per MS	**Task Description**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**Payable Milestone (Item No)**
1	Project Kick Off Meeting and Subcontracting	$9,335	$0	$9,335	$831	$0	$831	
2	Purchase & Characterize Pipe Material	$134,674	$15,107	$34,674	$146,108	$44,454	$140,562	31
3	Literature Review	$11,549	$0	$11,549	$8,669	$0	$8,669	
4	Testing of Dents on Welds & Corrosion Features	$188,507	$0	$157,363	$599,632	$25,934	$525,520	38, 41
5	Testing of Dents with Gouges	$150,020	$0	$150,020	$254,404	$62,476	$222,093	36, 39
6	Demonstration of Mechanical Damage Model Performance	$22,008	$0	$0	$10,930	$0	$0	
7	Industry Workshop	$12,030	$0	$0	$4,325	$0	$0	
8	Project Management and Reporting	$88,366	$1,834	$58,910	$43,959	$0	$1,692	40
	GRAND TOTAL	**$616,490**	**$16,941**	**$421,851**	**$1,068,858**	**$132,864**	**$899,367**	