FINAL REPORT

Contract Number: DTPH56-08-T-000011

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

Project WP#339: Structural Significance of Mechanical Damage

The letter transmits the Final Report for work completed under US DOT PHMSA Other Transaction Agreement (OTA) DTPH56-08-T-000011, Structural Significance of Mechanical Damage. The project was implemented to develop a detailed experimental database on how pipelines respond when affected by mechanical damage, caused by both external interference and rock dents. This full-scale testing program produced detailed experimental data to support the validation of improved burst and fatigue strength models to assess dents interacting with secondary features - gouges, corrosion, and welds. These data are needed to support the efforts of PHMSA and the pipeline industry to ensure safe operation of pipeline systems and to promote continuous improvements and focus on public safety.

The Final Report presents the activities completed to develop a detailed database of mechanical damage defects and evaluating the impact of those defects on the structural significance of operating pipelines. These data form the basis and input for further development and validation of mechanistic models previously developed to predict the conditions that lead to immediate (burst) or delayed failure under fluctuating pressure loading. The engineering tools and empirical and mechanistic (numeric) models currently used for assessing the significance of mechanical damage with secondary features are based on a number of assumptions rather than detailed experimental data. Improvements to the models are needed to avoid overly conservative assessments, promoting unnecessary maintenance, or the lack of required maintenance that could result in unexpected failures, which represent a significant environmental and safety concern for operating pipelines.

The project included the creation and full-scale testing of Dent+Gouge and Dents/Dents with secondary features (corrosion, on welds) using modern steels and vintage steels, with the vintage steels being from former in-service pipelines. The full-scale tests were highly instrumented to capture the level of detail needed for a range of parameters that are important to the development and validation of mechanical damage assessment models. The models that will be developed (by other efforts) should eventually be made available for pipeline integrity management.

The final report includes information and details of the testing already completed in the project, and are included in the attachments to this cover letter. It is built from information provided in the Quarterly Reports already provided during the project life and included in this final report. The following Appendix A and B summarize the final status of the Testing on Dents and Dent + Gouge research.

Electricore, PRCI, BMT Fleet Technology, GDF SUEZ appreciate the opportunity to work on this program with PHMSA. Please contact Electricore directly with any questions:

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Appendix A—Technical Details Testing on Dents[1] (Task 4)

The experimental testing for dents is being performed by BMT Fleet Technology Ltd (BMT) with support from Stress Engineering Services (SES) as a subcontractor. The original scope of work for the dent testing program consisted of the following primary activities:

- Developing a dent test sample matrix, consisting of 72 samples – these samples were divided between modern steel pipe (50 samples) and vintage steel pipe (22 samples).
- Creating dent samples using two indenter sizes of 2 and 4 in. nominal diameter. Three different dent depths are being created using indenter travel of 5%, 10% and 15% of the pipe diameter (note, these values are total indentation depth; the dents rebound following removal of the indenter and are actually shallower). The 5% and 10% dent depths are for restrained dents and 15% indenter travel is being used for creating unrestrained dents. The test matrix involves a combination of plain dents, dents interacting with welds, and dents interacting with simulated corrosion.
- Creating dents in unpressurized pipe specimens
- Testing duplicate specimens for each combination of variables
- Instrumentation of half the tests (36)
- Radiography of the three representative welds

The initial test matrix is presented in the summary table below.

Table 1: Initial Project Dent Test Matrix

Condition	Restrained		Unrestrained		
Pipe	X52 – 24"Dia x 0.312" thick	X70 – 24"Dia x 0.35" thick	X52 – 24"Dia x 0.312" thick	X70 – 24"Dia x 0.35" thick	New Material
Plain dents 24 tests	2 x 2" indenter 5% depth	4 x 4" indenter 10% depth	4 x 2" indenter 2 x 4" indenter 15% depth	4 x 2" indenter 2 x 4" indenter 15% depth	3 x 2" indenter 3 x 4" indenter 15% depth
Dent on girth weld 24 tests	2 x 2" indenter 5% depth	2 x 4" indenter 10% depth	3 x 2" indenter 3 x 4" indenter 15% depth	3 x 2" indenter 3 x 4" indenter 15% depth	4 x 2" indenter 4 x 4" indenter 15% depth
Dent on long seam 2 tests	2 x 2" indenter 5% depth				
Dent on metal loss 22 tests	3 x 2" indenter 5% depth	3 x 4" indenter 10% depth	2 x 2" indenter 2 x 4" indenter 15% depth	2 x 2" indenter 2 x 4" indenter 15% depth	4 x 2" indenter 4 x 4" indenter 15% depth

As the project progressed and the initial testing data generated were reviewed with the research team, there were a number of adjustments proposed. These adjustments resulted in an increase in test variables (dent shape, dent size, restrained dent tests for vintage pipes, indentation under pressure), and the quality of the test data (all tests in the present program were instrumented as compared to 50% of the tests). The changes include:

[1] Includes plain dents, dents on welds, and dents with metal loss

- Limiting duplicate testing and providing experimental data for a wider range of scenarios and mechanical damage conditions
- Adding shallower and blunter dents
- Increasing the range of indenter sizes from two to four
- Adding a number of tests where the indentation is carried out on pressurized pipe, compared to the tests carried out to date where all indentation is carried out at 0% pressure
- Full instrumentation of all test specimens and radiography examination of all girth welds
- Incorporating restrained dent tests on vintage pipe

The program completed 40 tests on Pipe A and B rather than the original total of 50 tests. The reduction included several of the duplicate specimens in the remaining girth weld test samples and reducing the number of samples for the dent with the metal loss portion of the test program. The total number of metal loss specimens was six. The maximum depth of the features was 20% of the wall thickness. The project reduces the total number of specimens included in the program to 62 specimens (compared to 72 tests in the original matrix).

The modified test matrix investigated a wider variety of dent geometries, including deeper unrestrained dents, shallower restrained dents, and blunter indenter sizes. It also maximizes the possible number of direct comparisons between the various dent parameters, and includes a number of dents to be made while the test pipe is under pressure. Moreover, the matrix does not include any duplicate tests. The difference in the original vintage pipe test matrix and the proposed vintage pipe test matrix is compared in the table below. The comparison of the old and the new matrix shows that the scope and the range of parameters that are being investigated have increased. The matrix has been developed with the following objectives in mind:

- The dent models can be calibrated and validated (dent shape, dent formation strains, cyclic strain range, and pressure versus strain/stress transfer functions) against a wider range of dent scenarios and therefore ensure its applicability covers the range of damage scenarios encountered by pipeline operators.

- Generate enough test data to develop suitable fatigue life trends based on dent depths, dent shapes and dent restraint condition. This will ensure that enough data and trends are available to investigate different life estimation approaches (stress life, strain life and crack growth approaches)

- Generate test data and evaluate the behavior and response of dents formed during pipe installation (zero pressure) as well as dents formed during service (dents formed under pressure).

Table 2: Comparison of the Original and the Final Test Variables for Vintage Pipe Full Scale Dent Testing

Parameters	Original Matrix	Final Matrix
Dent Depth, Unrestrained	1	2
Dent Depth, Restrained	0	3
Dent Size	2	4
Indentation under Pressure	0	2
Instrumentation of Tests	11	21
Test on Vintage Pipe	22	22

Table 3: Final Test Matrix for Vintage Pipe Material (Pipe C)

Specimen #	Pipe Material	Indenter Diameter (in)	Indenter Travel (%)	Dent Depth (%)	Dent Restraint	Interacting with	Indentation Pressure (%SMYS)	Initial Pressure Cycle (%SMYS)	Cyclic Pressure Range (%SMYS)	Weld Seam Location
41	C	2	5	5.1%	R	Plain	0	100%	10%-80%	N.A.
42	C	4	10	10.1%	R	Plain	0	100%	10%-80%	N.A.
43	C	2	7.5	7.5%	R	Plain	0	100%	10%-80%	N.A.
44	C	8	7.5	7.5%	R	Plain	0	100%	10%-80%	N.A.
45	C	8	7.5	7.5%	R	Plain	40%	100%	10%-80%	N.A.
46	C	12	5	5.1%	R	Plain	0	100%	10%-80%	N.A.
47	C	8	7.5	7.5%	R	Plain	80%	100%	10%-80%	N.A.
48	C	2	15	~2	U	Plain	0	100%	10%-80%	N.A.
49	C	2	10	10.0%	R	Plain	0	100%	10%-80%	N.A.
50	C	2	15	~2	U	Plain	40%	100%	10%-80%	N.A.
51	C	2	15	~2	U	Plain	80%	100%	10%-80%	N.A.
52	C	4	15	~2	U	Plain	0	80%	10%-80%	N.A.
53	C	12	20	~2	U	Plain	40%	80%	10%-80%	N.A.
54	C	12	15	~2	U	Plain	0	100%	10%-80%	N.A.
55	C	12	20	~2-5	U	Plain	80%	80%	10%-80%	N.A.
56	C	4	20	~2	U	Plain	0	100%	10%-80%	N.A.
57	C	12	20	~2	U	Plain	0	80%	10%-80%	N.A.
58	C	2	15	~2	U	GW	0%	100%	10%-80%	offset
59	C	12	20	~2	U	GW	0%	80%	10%-80%	c/l
60	C	2	7.5	7.5	R	GW	0%	100%	10%-80%	offset
61	C	8	7.5	7.5	R	GW	0%	100%	10%-80%	offset
62	C	12	20	~2	U	Plain	80%	100%	10%-80%	N.A.

Table 4: Test Matrix and Result Summary for Dent Fatigue Tests

Spec. #	Pipe Mat	Indenter Diameter (in)	Initial Indenter Travel (%)	Dent Condition	Interacting with	Indentation Pressure (%SMYS)	Firstl Press. Cycle (%SMYS)	Cyclic Press. Range (%SMYS)	Secondary Feature Location	Cycles to Failure
1	A	2	5	R	Plain	0%	100%	10%-80%	N.A.	6948
2	A	2	5	R	Plain	0	100%	10%-80%	N.A.	38685
3	B	4	10	R	Plain	0	100%	10%-80%	N.A.	6886
4	B	4	10	R	Plain	0	100%	10%-80%	N.A.	16234
5	B	4	10	R	Plain	0	80%	10%-80%	N.A.	2531
6	B	4	10	R	Plain	0	80%	10%-80%	N.A.	3359
7	A	2	15	U	Plain	0	100%	10%-80%	N.A.	21103
8	A	2	15	U	Plain	0	100%	10%-80%	N.A.	28211
9	A	2	15	U	Plain	0	80%	10%-80%	N.A.	6825
10	A	2	15	U	Plain	0	80%	10%-80%	N.A.	9116
11	A	4	15	U	Plain	0	100%	10%-80%	N.A.	15063
12	A	4	15	U	Plain	0	100%	10%-80%	N.A.	27575
13	B	2	15	U	Plain	0	100%	10%-80%	N.A.	13263
14	B	2	15	U	Plain	0	100%	10%-80%	N.A.	15065
15	B	2	15	U	Plain	0	80%	10%-80%	N.A.	4035
16	B	2	15	U	Plain	0	80%	10%-80%	N.A.	4684
17	B	4	15	U	Plain	0	100%	10%-80%	N.A.	11415
18	B	4	15	U	Plain	0	100%	10%-80%	N.A.	15949
19	A	2	5	R	Long Seam	0	100%	10%-80%	C.L.	32282
20	A	2	5	R	Long Seam	0	100%	10%-80%	C.L.	24919
21	A	2	5	R	Girth Weld	0	100%	10%-80%	2" Offset	66871
22A	A	4	10	R	Girth Weld	0	100%	10%-80%	2" Offset	66429
23	B	4	10	R	Girth Weld	0	100%	10%-80%	2" Offset	12722
24	B	4	10	R	Girth Weld	0	100%	10%-80%	2" Offset	16278
25	A	2	15	U	Girth Weld	0	100%	10%-80%	C.L.	19063
26	A	4	10	R	Metal Loss	0	100%	10%-80%	C.L.	40832
27	A	2	15	U	Girth Weld	0	100%	10%-80%	2" Offset	18633
28	A	2	15	U	Girth Weld	0	100%	10%-80%	2" Offset	16107
29	A	4	15	U	Girth Weld	0	100%	10%-80%	2" Offset	14400
30	A	4	10	R	Metal Loss	0	100%	10%-80%	C.L.	31179
31	B	2	15	U	Girth Weld	0	100%	10%-80%	2" Offset	9890
32	B	2	15	U	Girth Weld	0	100%	10%-80%	2" Offset	9506
33	B	4	15	U	Girth Weld	0	100%	10%-80%	2" Offset	9386
34	B	4	15	U	Girth Weld	0	100%	10%-80%	2" Offset	9871
35	B	4	15	U	Girth Weld	0	100%	10%-80%	C.L.	19959
36	B	4	15	U	Girth Weld	0	100%	10%-80%	C.L.	15568
37	A	4	15	R	Metal Loss	0	100%	10%-80%	C.L.	42159
38	A	4	15	U	Metal Loss	0	100%	10%-80%	C.L.	32963
39	B	4	5	R	Metal Loss	0	100%	10%-80%	Offset	7559
40	B	4	15	U	Metal Loss	0	100%	10%-80%	Offset	6504
41	C	2	5	R	Plain	0	100%	10%-80%	N.A.	69099
42	C	4	10	R	Plain	0	100%	10%-80%	N.A.	69393
43	C	2	7.5	R	Plain	0	100%	10%-80%	N.A.	30604
44	C	8	7.5	R	Plain	0	100%	10%-80%	N.A.	54036
45	C	8	7.5	R	Plain	40%	100%	10%-80%	N.A.	58532
46	C	12	5	R	Plain	0	100%	10%-80%	N.A.	125525
47	C	8	7.5	R	Plain	80%	100%	10%-80%	N.A.	61865
48	C	2	15	U	Plain	0	100%	10%-80%	N.A.	23482
49	C	2	10	R	Plain	0	100%	10%-80%	N.A.	30604
50	C	2	15	U	Plain	40%	100%	10%-80%	N.A.	16600
51	C	2	15	U	Plain	80%	100%	10%-80%	N.A.	12131
52	C	4	15	U	Plain	0	80%	10%-80%	N.A.	9226
53	C	12	20	U	Plain	40%	80%	10%-80%	N.A.	18636
54	C	12	15	U	Plain	0	100%	10%-80%	N.A.	47702
55	C	12	20	U	Plain	80%	80%	10%-80%	N.A.	21018
56	C	4	20	U	Plain	0	100%	10%-80%	N.A.	15473
57	C	12	20	U	Plain	0	80%	10%-80%	N.A.	14091
58	C	2	15	U	Girth Weld	0%	100%	10%-80%	1.25" offset	4815
59	C	12	20	U	Girth Weld	0%	80%	10%-80%	C/L	6126
60	C	2	7.5	R	Girth Weld	0%	100%	10%-80%	0.75" offset	32580
61	C	8	7.5	R	Girth Weld	0%	100%	10%-80%	1.5" offset	33451
62	C	12	20	U	Plain	80%	80%	10%-80%	NA	12861

Appendix B—Testing on Dent+Gouge Defects (Task 2 and 5)
Material characterization of the second vintage pipe is performed by GDF SUEZ. This work includes the full material characterization of this vintage pipe:

- Chemical Composition
- Hardness (Base Material, Weld Material, HAZ)
- Microstructure
- J Curves
- Machined round bar tensile tests
- Effects of pre-strain on toughness
- Machined sub-size flat specimens
- Charpy V notch toughness
- Kinematic hardening behavior

The testing program for Dent +Gouge defects is being performed by GDF SUEZ, with the defects being introduced using the Pipe Aggression Rig. The work completed to date has included testing on modern steel with five different types of Dent+Gouge defects created using both highly dynamic aggression (defect Types 1.1.1b, 1.2.1b, and 2.1.1 in the table below) and a slower aggression mode where the gouge is shallower and the dent more severe than the dynamic aggression conditions (defect Types 1.3.1 and 2.2.1) (Table 5). Each defect type created is then subjected to a series of detailed material characterization tests and burst and fatigue testing, with the burst and fatigue test being highly instrumented to provide detailed and comprehensive measurement data for the development of the improved severity assessment models.

Table 5: Dent and Gouge tests matrix

	MD 4-1					**DOT**	
Pipe number	**Pipe 1** (modern steel X52)			**Pipe 2** (modern steel X65)		**Pipe 3DG** (vintage steel)	
Defect type	Type 1	Type 2	Type 3	Type 1 or 2	Type 2 or 3	Type 1	Type 2
Defect 1: Detailed characterization	**Defect 1.1.1**	**Defect 1.2.1**	**Defect 1.3.1**	**Defect 2.1.1**	**Defect 2.2.1**	**Defect 3DG.1.1**	**Defect 3DG.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 3DG.1.2**	**Defect 3DG.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 3DG.1.3**	**Defect 3DG.2.3**

(green)	**Completed Tests**
(pink)	**Vintage Pipe Tests not completed**

Data collected to date on the burst and fatigue models created have been communicated to the full project team and the modeling SMEs working on the related mechanical damage modeling projects.

Tables 6 and 7 respectively summarize results of burst and fatigue tests on modern pipes 1 and 2 that were created on pressurized pipes.

Table 6: Results of burst tests on modern pipes

Pipe number	Defect number	Type of mechanical aggression for defect creation	Dent depth without pressure (%)	Pressure during defect creation (bar)	Burst pressure (bar)	Failure mode
Pipe 1	Defect 1.1.2	Highly Dynamic aggression	1,6	85	133	Ductile rupture in the pipe body
	Defect 1.2.2	Highly Dynamic aggression	2,6	85	110	Ductile rupture in defect
	Defect 1.3.2	Slower dynamic aggression	5,9	30	131	Ductile rupture propagation from defect
Pipe 2	Defect 2.1.2	Highly Dynamic aggression	1,6	85	185	Ductile rupture propagation from defect
	Defect 2.2.2	Slower dynamic aggression	5,2	20	194	Ductile rupture propagation from defect

Table 7: Results of fatigue tests on modern pipes

Pipe number	Defect number	Type of mechanical aggression for defect creation	Dent depth without pressure (%)	Pressure during defect creation (bar)	Fatigue amplitude Pmin-Pmax (bar)	Number of cycles at failure	Failure mode
Pipe 1 X52 grade	Defect 1.1.3	Highly Dynamic aggression	1,6	85	45 - 85	10.869	Leak in defect
	Defect 1.2.3	Highly Dynamic aggression	2,6	85	45 - 85	5.200	Leak in defect
	Defect 1.3.3	Slower dynamic aggression	5,9	30	53 - 93	20.494	Leak in defect
Pipe 2 X70 grade	Defect 2.1.3	Highly Dynamic aggression	1,6	85	88 - 128	17.700	Leak in defect
	Defect 2.2.3	Slower dynamic aggression	5,2	20	20 - 60	2.007	Leak in defect

Other main results of this study include:

- Defects created by highly dynamic aggression and by slower dynamic aggression are very different :
    - Highly dynamic aggression introduces at the gouge bottom hard layers associated with micro-cracks (Figure 1). The first hard layer at the gouge surface contains tooth steel whereas the second hard layer below is the pipe steel that underwent straining and thermal treatment due to heating during aggression.

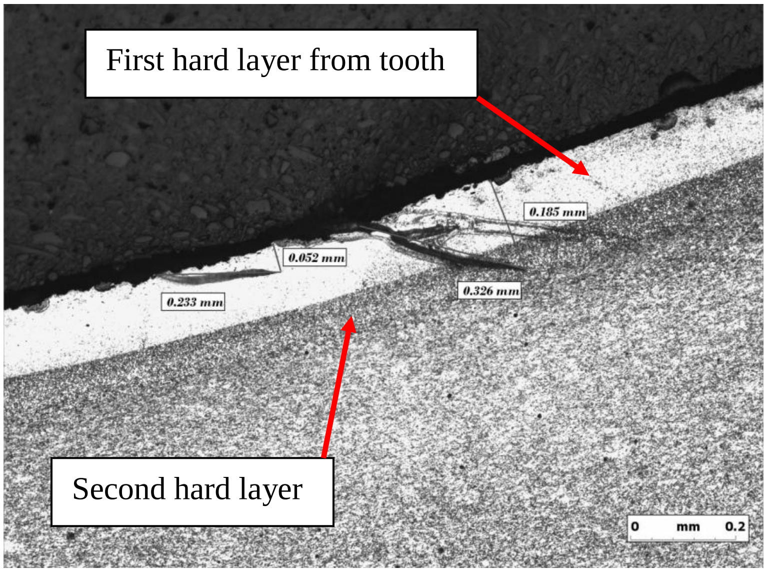

Figure 1: Hard layers and micro-cracks at the gouge surface in a defect created by highly dynamic aggression

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    - Defects from slower dynamic aggression do not exhibit very hard layers and micro-cracks at the gouge surface as seen in Figure 2 below.

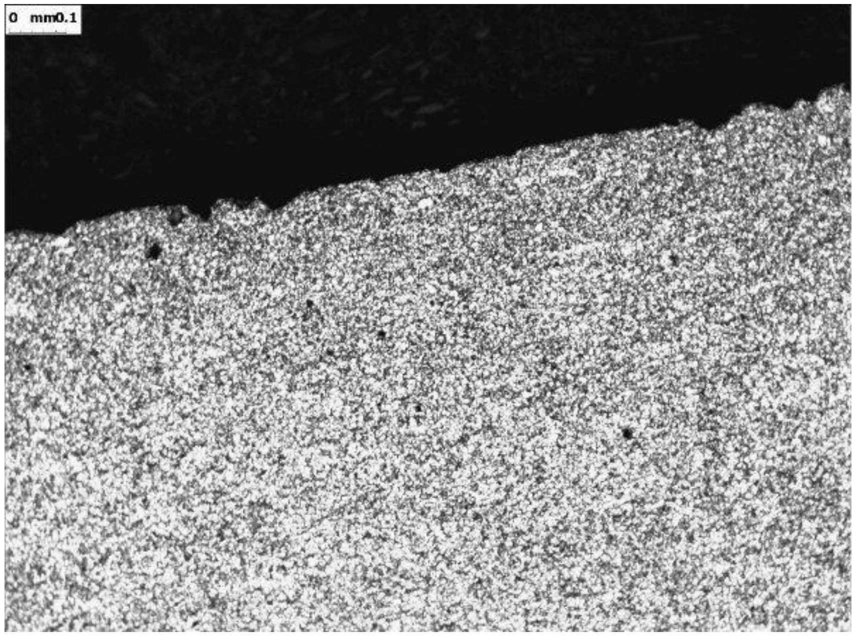

Figure 2: Microstructure at the gouge surface of a defect created by slower dynamic aggression

- Defects created by slower dynamic aggression with **worn teeth** and **lower internal pressure** lead to deeper dents. As a consequence, during pressure increase, dent pop-up and bulging is significant for these defects as shown in Figure 3 below.

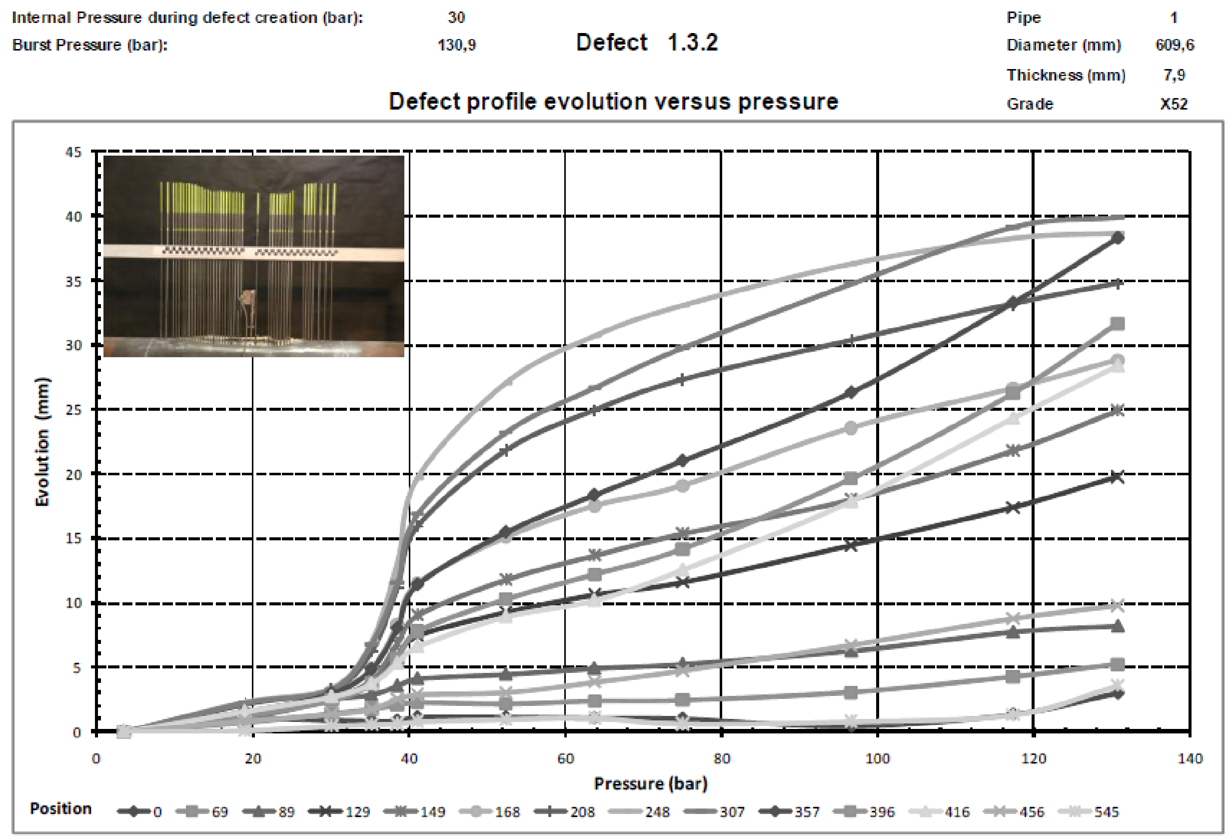

Figure 3: Dent pop-up followed by significant bulging for pressure increase between 30 bar and 50 bar

- Dent bulging has a very significant impact on the remaining defect fatigue life time. The dent pops up and bulges above the dent creation pressure. If the defect is submitted to pressure swings above the dent pop-up / bulging pressure range, that means at high mean pressure, the remaining fatigue life is significant (20.494 cycles for defect 1.3.3, see Table 3 above). But if the same type of defect is submitted to a lower mean pressure in the pressure range of dent pop-up / bulging, the dent fatigue lifetime is reduced by one order of magnitude (2.007 cycles for defect 2.2.3, see Table 3 above). So, fatigue loading in the bulging pressure range, or just above the indentation pressure, may significantly reduce the expected fatigue life of the dent and gouge defects. These results should be confirmed on a larger sample of steel grades and dent shapes.