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REPAIR OF MECHANICALLY-DAMAGED PIPES USING ARMOR PLATE PIPE WRAP

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SUMMARY

This paper details the testing of mechanically-damaged pipes repaired using Armor Plate Pipe Wrap (APPW). In this discussion, mechanical damage means local indentation of a pipe with an external gouge. This type of defect results in reduction of structural integrity when internal pressure is applied both statically and in a cyclic manner. A significant level of research on mechanical damage has been conducted over the past twenty years based upon the observation that third-party damage is the leading cause of pipeline failures in the United States. More recently, efforts have addressed the effects of cyclic pressure service on mechanical damage and the number of cycles required for the development of leaks.

In this study, mechanical damage was created by installing dents in pipes that were previously gouged by an end mill. The gouge depths and dent depths were 15 percent of the pipe wall thicknesses and diameters, respectively. Two pipe sizes and grades were used. One being 12.75-in x 0.188-in, grade X52 and the other bring 12.75-in x 0.375-in, grade X42. Four defects were created in each of the two pipe samples, giving a total of eight defects in the test program. In each sample one defect was not repaired, two were repaired by grinding and installation of APPW, and the fourth defect was repaired by grinding, installation of APPW plus installation of a stainless steel clamp. Internal pressure was cycled in each samples at a range of 100 percent of the maximum operating pressure (MOP) until failure occurred in each defect. As failures occurred, the failed sections were cut out and the remaining segments welded together so that additional cycle testing could occur.

In terms of failure data, the following trends were observed. Samples *repaired by grinding* had fatigue lives that were approximately 10 times those of *unrepaired dents and gouges*. Those defects that were repaired by *grinding and APPW* had fatigue lives that were approximately 1,000 times those of *unrepaired dents and gouges*. Slight improvements were obtained over the grinding/APPW repair with the installation of the Armor Plate stainless steel clamp. The minimum cycles to failure at 50 percent MOP for any given defect was greater than 100,000 cycles. The conclusion based upon these test results is that dents and gouges can be repaired using Armor Plate Pipe Wrap in conjunction with grinding when considering the normal cyclic pressure loads for most liquid and gas transmission pipelines.

INTRODUCTION

Because third-party mechanical damage to both liquid and gas transmission pipelines is a serious problem, a considerable amount of research has been conducted to address mechanical damage as it relates to pipeline integrity. The bulleted items below represent the major U. S. works in this area. These research programs have considered both hydrostatic as well as cyclic pressure loadings.

Battelle Memorial Institute (Battelle) has been active in works relating to pipeline research. In the 1960s and 1970s they received a significant amount of the research money available from the Pipeline Research Committee at the American Gas Association. Numerous works were produced by Battelle in this area (Maxey, 1986, 1987 and Eiber et al., 1981).

In the early 1990s a research program was funded by the Pipeline Research Committee at the American Gas Association to address the cyclic pressure effects on the fatigue life of pipelines with plain dents. This program was conducted by Stress Engineering Services, Inc. (Fowler et al., 1994). Based upon the insights gained with this program, additional research was conducted to address dents combined with gouges and dents combined with welds. Dents were installed using a flat plate indenter with no internal pressure. The predominant conclusion was that plain smooth dents with depths less than 5 percent of the pipe's outer diameter should not be a problem. However, the experimental results showed that dents with gouges have a significant impact on fatigue life, with gouge depth being the critical issue. Finite element efforts were also used to develop stress concentration factors for estimating the fatigue life of dents given a specified dent depth and cyclic pressure range.

Another research program was funded by the Pipeline Research Committee International (PRCI) to address the repair of mechanical damage (dents with minor scratches) by grinding (Kiefner et al., 1999). This program was conducted jointly by Kiefner & Associates, Inc. and Stress Engineering Services, Inc. Dents were installed with internal pressure (60 percent SMYS) and a slender 1-in wide bar was used to indent the pipes. The objective was to determine which defects can be repaired by grinding and the best procedure for doing so. In all testing, the defects were conducted in pairs so that the repaired defects could be compared to the unrepaired defects. Results indicated that shallow unrepaired gouge depths (less than 5 percent of the pipe wall) combined with dents with depths less than 10 percent of the pipe's diameter had burst strengths that exceeded 100 percent SMYS. In terms of repair, grinding proved to be a viable means of repair as long as the repair did not reduce the wall thickness by more than 20 percent. The cyclic pressure tests indicated that fatigue life was directly related to dent and gouge depths, with grinding being a viable means of repair. The results of this effort showed that repair by grinding is a viable method for repairing pipes that contain dents with minor scratches.

The European Pipeline Research Group (EPRG) has also been active in funding research addressing the effects of dents on gouges on pipeline serviceability (Corder et al., 1995).

In 1996 the American Petroleum Institute funded a research program to address the effects of smooth and rock dents on liquid petroleum pipelines (Alexander et al., 1997). This program was conducted jointly by Stress Engineering Services, Inc. and Kiefner & Associates, Inc. The incentive for the research was to avoid replacing or repairing pipe affected by such dents if they do not constitute a threat to pipeline serviceability. Rock dents were tested in a constrained fashion, while the smooth dents were permitted to reround with increased pressure after denting. The conclusion was that pipeline operators need not be concerned about the short-term consequences of truly smooth, unconstrained dents. This is in part due to the fact that unconstrained dents are unlikely to have dent depths greater than 5 percent in a pipeline that has been pressurized to levels of 72 percent SMYS or more. Concern arises only if the dent is to be subjected to aggressive cyclic pressure service over a long period of time.

One incentive for conducting research on mechanical damage is to develop operating guidelines and codes that ensure safe operation. Although it is recognized that dents combined with gouges have a serious bearing on pipeline operation, the question arises as to whether the existing standards are too restrictive in requiring that certain defects be removed or repaired. As specified in ASME B31.8, para. 841.243(c), any dent which is greater than 2 percent of the pipe diameter must be removed from a pipe that operates at more than 40% of the specified minimum yield strength. The standards also state that all gouges must be removed in para. 841.242(a). The primary aim of the original research conducted by StressEngineering Services, Inc. (Fowler et al., 1994) in studying dents and gouges was to determine if these standards were too conservative.

Based upon current industrypractices in repairing damaged pipe. The *Pipeline Repair Manual* developed with funding from the Pipeline Research Committee International (Kiefner et al., 1994) provides the following list of options,

1. Removal and replacement of a defective segment
2. Grinding
3. Deposited weld metal
4. Full-encirclement sleeves (Type A and Type B)
5. Defect repair using composite reinforcement sleeve
6. Mechanical bolt-on clamps
7. Hot tapping
8. Patches and half soles.

Based upon these previous developments and the effectiveness in using Armor Plate Pipe Wrap to repair corrosion (Alexander et al., 1998a), it seemed appropriate to evaluate APPW for repairing mechanical damage. This paper provides the test methodology and results associated with this effort.

TEST METHODS

Prior to testing, pipe samples were selected based upon desired pipe geometries. In many of the pipe research programs focused on mechanical damage, 12-in diameter pipes have been used. Factors such as ease in handling and relatively small sample volume contributed to their selection. For facilitating comparison of previous fatigue data with the failures acquired in the Armor Plate program, 12-in nominal diameter pipe was used. Two pipe sizes were chosen,

- Sample A, 12.75-in x 0.188-in, grade X52, D/t = 68 (pipe diameter to wall thickness ratio)
- Sample B, 12.75-in x 0.375-in, grade X42, D/t = 34 (pipe diameter to wall thickness ratio)

In each of the two pipe samples, four defects were installed. While there are numerous methods for installing dents and dents with gouges in pipelines, the procedure used in testing the Armor Plate system complemented the methods employed by Fowler in the AGA sponsored-research program (Fowler et al., 1994). The basic procedures employed in testing were as follows,

1. Install end caps on the pipe.
2. Install 6-in long longitudinal gouges using an end mill in pipe at selected locations at depth of 15 percent pipe wall (gouge profile similar to Charpy V-notch configuration with 90° bevel and 0.002-in radius).
3. Install 6-in long dent using flat plate at 15 percent of pipe diameter, offsetting edge of indenter 2-in from end of gouge (results in a total defect length of 8-in).
4. Allow dent to reround with removal of indenter and measure longitudinal profile.
5. Apply internal pressure equal to 60 percent of the minimum specified yield strength pressure and hold for 30 minutes. Return to 0 psi and measure dent profile.

For the repaired sections, the following steps were used.

1. Remove gouge by grinding with a hand-held grinder. Use dye-penetrant to ensure removal of crack at base of gouge. Measure remaining wall thickness using ultrasonic methods.
2. Fill dented region with epoxy-putty material to restore circular profile to outside surface of the dented pipe.
3. Install Armor Plate Pipe Wrap. In repairing mechanical damage, the minimum thickness of the wrap should be at least 1.5 times the thickness of the pipe wall.
4. When installing Armor Clamp, four layers of APPW should be installed.

Table 1 provides a list of the defects and repair configurations associated with the two pipe samples.

Figure 1 shows the indenter test rig used to install the dents, while **Figure 2** provides a close-up view of the indenter plate positioned on the pipe. The denting procedure was repeated to create four dents in each pipe sample. In the process of creating the dents measurements were made to acquire the dent profile and dent depth. **Table 2** provides the dent depth measurements for all of the test samples, while **Figure 3** plots the axial profile for Sample A4 and Sample B4. Note the significant level of rerounding that occurs in the dented region as a result of internal pressurization.

Table 3 provides the changes in wall thickness that resulted from the grinding process. The significance in the remaining wall is that one can determine the extent of the cracked material in comparison to the original depth of the gouge.

After the dents were installed and the gouges repaired by grinding, the Armor Plate Pipe Wrap sleeves were installed. The information in **Table 1** provides the specific number of wraps installed on each sample. The general rule of thumb for repairing mechanical damage (after gouge removal) is for the thickness of the wrap to be 1.5 times the thickness of the pipe wall thickness. Each layer of the wrap is approximately 1/16-in thick. Four layers of APPW were used in conjunction with the clamps. **Figure 4**, **Figure 5** and **Figure 6** show different stages of the wrap installation process.

While the focus of this testing was on the use of Armor Plate in repairing mechanical damage, the recent development of a stainless steel clamp by Armor Plate, Inc. (used in conjunction with the composite wrap materials) was implemented into the fatigue test program. One clamp was installed on each of the pipe samples. **Figure 7** is a photograph of one of the clamps. As seen, the clamp is comprised of two halves that are bolted together. Both Sample A1 and Sample B1 involved four layers of APPW in addition to the clamps. The clamps are fabricated from 1/8-in 316 stainless steel material and are bolted together using six 3/4-in bolts. Prior to their installation, the APPW sleeves were applied and permitted to cure. The surfaces of the wrap were ground smooth and grease was applied to reduce friction during the bolt-tightening process. The bolts were tightened to 125 ft-lbs which corresponded to an approximate bolt stress of 52,000 psi.

Following the repair of the dents and gouges, the two pipe samples were subjected to cyclic pressures. The selected pressure ranges were based upon percentages of the Maximum Operating Pressure (MOP) which was assumed to be 72 percent of the SMYS for each pipe. The applied pressure ranges were both 100 percent of the MOP which corresponded to the following ranges (100 psi minimum permitted by pumping unit).

- Sample A, 100 - 1,200 psi
- Sample B, 100 - 1,880 psi

The samples were cycled until a failure developed in one of the damaged areas. The failure was then cut out and the remaining pipe segments were welded together. This process was continued until all eight samples had been tested.

TEST RESULTS

In terms of test results and their presentation, the essential element is cycles to failure for each test sample. The evaluation of the Armor Plate system is directly related to the improvement in fatigue life for those samples repaired using APPW. As will be shown, significant improvement is derived in application of Armor Plate. Additional benefits are derived with installation of the stainless steel clamp.

Two modes of presentation are used. First, data is presented in tabular form. **Table 4** presents the raw fatigue data for the applied pressure range as well as a modified fatigue value that corresponds to a lower applied cyclic stress range. The second method of presentation is **Figure 8**, a plot showing cycles to failure for the test samples. Also included in this plot are test data from other research programs concerned with dents containing gouges (Alexander et al., 1998 and Fowler et al., 1994).

Tabulated Test Results

Table 4 provides the cycles to failure for the eight samples tested in this program. As noted in the table, installation of APPW significantly increased the fatigue life when compared to the unrepaired test samples.

Plotted Test Results

The benefit derived in plotting the fatigue results from this project are that direct comparisons can be made with existing fatigue data on mechanical damage. As stated previously, work conducted for the American Gas Association (Fowler et al., 1994) and the Gas Research Institute (Alexander et al., 1998) provide the key data for making this type of comparison.

Figure 8 plots the cycles to failure for the samples repaired using APPW as well as the data for the two stainless steel clamps. Four sets of data are plotted.

- Unrepaired dents with gouges
- Dents and gouges repaired via grinding
- Dents and gouges repaired by grinding and installation of APPW
- Dents and gouges repaired by grinding, installation of APPW, and stainless steel clamp

In terms of failure data, the following trends were observed.

- Samples *repaired by grinding* had fatigue lives that were approximately 10 times those of *unrepaired dents and gouges*.
- Those defects that were repaired by *grinding and APPW* had fatigue lives that were approximately 1,000 times those of *unrepaired dents and gouges*.
- Slight improvements were obtained over the grinding/APPW repair with the installation of the stainless steel clamp.

The minimum cycles to failure at 50 percent MOP for any of the repaired defects (Sample B2) was approximately 200,000 cycles, while the maximum cycles to failure at 50 percent MOP was more than 1.6 million cycles.

DISCUSSION OF RESULTS

This section of the paper briefly discusses some aspects of the test results and how they apply to the operation of actual pipelines. The following concepts are discussed,

- Repair by grinding
- Interpretation of fatigue data
- Location of failures

Repair by Grinding

To date, the most significant body of work relating to repair of mechanical damage by grinding was conducted for the Pipe Research Committee International by Kiefner and Alexander (Kiefner et al., 1999). This program focused on repair by grinding in terms of both hydrostatic and cyclic pressure loading. This previous research effort relates to the use of APPW in repairing mechanical damage because removing the material near the gouge is a key component of the repair process. The presence of the gouge in the dent results in cracks at the base of the gouge that develop during the rerounding process with increasing internal pressure. When the cracks are not removed, they continue to grow in response to increasing internal pressure (as in a quasi-static burst test) or with the application of repeated pressure cycles (as in a fatigue test). Recent research has validated this phenomenon as well as the use of grinding as a repair method (Kiefner et al., 1999). In this project, the gouges were removed using a hand-held grinder. Liquid dye penetrant was used to verify the removal of the cracked material at the base of the gouge.

The PRCI final report provided a section entitled *Guidelines for Repair by Grinding*. The major concepts presented from this section of the report are outlined below and discuss topics such as pressure reduction, cleaning, characterizing the visual extent of the damage, measuring the wall thickness of the pipe, and grinding and inspecting the repaired area.

- Mechanical damage is the most serious type of defect present in most pipelines. It is unlikely that the effect of a given gouge and dent defect on the remaining strength of the pipe can accurately be determined. For this reason, it is prudent to lower the operating pressure of the pipeline during both the inspection and repair phases.
- In order to properly inspect and characterize the pipe and the defect it is necessary to remove all coating, soil, corrosion products, and other debris from the vicinity of the defect. This is necessary so that no part of the gouge or the dent will be overlooked; all of it must be addressed to assure an adequate repair. A straight-edge should be used to measure the axial profile of the dent and if possible, calipers should be used to measure the overall pipe diameters relative to the dent. The wall thickness should be measured by means of an ultrasonic method.

- Metal removal by grinding should be done gradually. The ideally safe approach to grinding an axially oriented gouge with a disk grinder is to orient the wheel so it removes metal in the circumferential direction (across the gouge). The grinding should not be continued if more than 40 percent of the wall thickness required for design purposes will be removed. If the 40 percent threshold is reached before the gouge or any associated cracking disappears, repair by grinding should cease and another repair method should be applied. If the grinding required to remove all damage including cracks passes the 20 percent (of required wall thickness) threshold at any point and the depth of the groove at all points is less than or equal to 40 percent, the length of the groove between the extreme points where metal removal begins and ends should be measured and should not exceed L (equation based upon Canadian Standard, *Z662-96, Oil and Gas Pipeline Systems*, Paragraph 10.8.2.2.4)

$$L = 1.12\sqrt{Dt}\left(\left(\frac{a/t}{1.1a/t - 0.11}\right)^2 - 1\right)^{1/2}$$

D = outside diameter of pipe
t = wall thickness required for design
a = t minus minimum remaining thickness determined by ultrasonic measurement.

The width of the ground area (i.e., the circumferential extent) need not be limited unless there is an unusual source of axial stress on the pipeline.

Interpretation of Fatigue Data

The intent of this section of the paper is to discuss the cycles to failure for the test samples and how these numbers can be applied to actual operating pipelines. As discussed previously, the applied pressure cycles corresponded to 100 percent of the maximum operating pressure. While most pipelines will experience pressure levels at this level, it is unlikely that they are applied frequently. Liquid pipelines tend to experience more pressure cycles (and at larger ranges) than do gas transmission pipelines.

Conversion of cycles based upon stress range involves use of Miner's Rule and an *nth*-ordered relationship between stress and cycles to failure (characteristically *n* is between 3 and 4). Consider in our test program where the pressure range is 100 percent MOP. What is the calculated cycles to failure if the pressure level is changed to 50 percent MOP? The following equation permits this calculation and is based on Miner's Rule and a *4th*-ordered relationship between stress and cycles to failure.

$$N_2 = N_1 \cdot \left[\frac{\Delta P_2}{\Delta P_1}\right]^{-4}$$

where:

N_1	Cycles to failure assuming a pressure range of ΔP_1
N_2	Cycles to failure assuming a pressure range of ΔP_2
ΔP_1	Pressure range #1
ΔP_2	Pressure range #2

The cycles to failure assuming a pressure range of 50 percent MOP using known cycles to failure and pressure range (N_1 and ΔP_1, respectively) is calculated as follows.

$$N_2 = N_1 \cdot \left[\frac{50}{100}\right]^{-4} = 16N_1$$

Hence, reducing the applied pressure by 50 percent means that the fatigue life is increased by a factor of 16 times. An entire series of calculation can be performed by modifying the assumed pressure range. The previous data presented in **Table 4** uses this methodology.

To develop a relationship between the cycles to failure and years of service in an actual pipeline, consider Sample B2. This sample had the lowest number of cycles to failure, corresponding to 196,416 cycles with ΔP equal to 50 percent MOP. For an imposed safety factor, divide this number by 20, which gives 9,820 cycles. If a pipeline is assumed to have an applied pressure range of 50 percent MOP applied every other day, the fatigue life for repair (using the modified Sample B2 data) is approximately 54 years. While there are no fixed number of cycles per year that exist on any given pipeline, as a minimum this methodology can be employed to estimate the years of service a repair can withstand for a given set of operating conditions.

Location of Failures

Figure 9 and **Figure 10** show the failure locations for two of the repaired samples. **Table 5** lists the location of the cracks the developed as a result of the fatigue testing. It is interesting to note that most of the cracks developed away from the location of the original gouge. This observation is important for two reasons. First, it indicates that the grinding procedure was effective in removing the cracked material. Secondly, it indicates that the composite sleeve provided enough reinforcement so that fatigue cracks did not develop in the area of the pipe with the thinnest remaining wall.

COMMENTS AND CLOSURE

The primary aim of the fatigue testing of mechanical damage repair using Armor Plate Pipe Wrap was to determine the increase in fatigue life when compared to unrepaired and ground-only repairs. While a significant level of fatigue testing has been done on plain dents and dents with gouges, little effort has been made to address the effects of sleeves on the repair of mechanical damage. The primary reason for this missing body of information is that many companies choose to completely remove the damaged sections of pipe or install welded full encirclement sleeves. Their reasons for making such decisions are prudent based upon the available information to date; however, the use of composite sleeves and grinding in repairing mechanical damage has technical merit. The body of work reported herein contributes to the missing information in this area.

Specifically in terms of the benefits derived in application of Armor Plate Pipe Wrap, samples *repaired by grinding* had fatigue lives that were approximately 10 times those of *unrepaired dents and gouges.* Those defects that were repaired by *grinding and APPW* had fatigue lives that were approximately 1,000 times those of *unrepaired dents and gouges.* Slight improvements were obtained over the grinding/APPW repair with the installation of the stainless steel clamp. Considering that the minimum cycles to failure at 50 percent MOP was greater than 100,000 cycles, even with an applied factor of safety, this value far exceeds the number of cycles a typical gas or liquid transmission pipeline will see in its lifetime.

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Table 1 Dent and gouge sample configuration

Sample Number	Pipe Geometry	Gouge Depth	Dent Depth	Repair Configuration
A1	12.75 x 0.188	15% (0.028-in)	15% (1.9-in)	Gouge ground, 4 wraps of APPW, install clamp
A2	12.75 x 0.188	15% (0.028-in)	15% (1.9-in)	Gouge ground, 5 wraps of APPW
A3	12.75 x 0.188	15% (0.028-in)	15% (1.9-in)	Gouge ground, 5 wraps of APPW
A4	12.75 x 0.188	15% (0.028-in)	15% (1.9-in)	No repair
B1	12.75 x 0.375	15% (0.056-in)	15% (1.9-in)	Gouge ground, 4 wraps of APPW, install clamp
B2	12.75 x 0.375	15% (0.056-in)	15% (1.9-in)	Gouge ground, 9 wraps of APPW
B3	12.75 x 0.375	15% (0.056-in)	15% (1.9-in)	Gouge ground, 9 wraps of APPW
B4	12.75 x 0.375	15% (0.056-in)	15% (1.9-in)	No repair

Notes:
1. Gouge depth based upon percentage of nominal pipe wall thickness
2. Dent depth based upon percentage of nominal pipe diameter

Table 2 Dent depth measurements made during denting process

Sample Number	Target Dent Depth (inches)	Interim Dent Depth (inches)	Residual Dent Depth (inches)
A1	1.9	0.778	0.276
A2	1.9	0.690	0.234
A3	1.9	0.561	0.218
A4	1.9	0.897	0.295
B1	1.9	1.027	0.490
B2	1.9	1.052	0.473
B3	1.9	0.991	0.449
B4	1.9	1.017	0.476

Notes:
1. *Target dent depth* corresponds to depth the indenter was pushed into pipe during denting (no internal pressure)
2. *Interim dent depth* is the depth resulting from elastic rebound after the indenter was removed
3. *Residual dent depth* is the dent depth remaining after the samples were pressurized to 60 percent SMYS (920 psi for Sample A and 1,482 for Sample B)

Table 3 Wall thickness measurements before and after grinding

Sample Number	Gouge Depth	Wall thickness before grinding	Wall thickness before grinding	Material removed due to grinding
A1	15% (0.028-in)	0.187	0.146	0.041
A2	15% (0.028-in)	0.186	0.155	0.031
A3	15% (0.028-in)	0.188	0.151	0.037
A4	15% (0.028-in)	0.188	Sample not ground	
B1	15% (0.056-in)	0.381	0.322	0.059
B2	15% (0.056-in)	0.380	0.318	0.062
B3	15% (0.056-in)	0.371	0.309	0.062
B4	15% (0.056-in)	0.383	Sample not ground	

Notes:
1. Wall thickness measurements made using a hand-held ultrasonic meter

Table 4 Cycles to failure for test samples

Sample Number	Cycles to Failure $\Delta P = 100\%$ MOP	Cycles to Failure $\Delta P = 50\%$ MOP(1)	Notes
A1	100,123	1,601,968	4 layers of APPW, stainless clamp
A2	61,558	984,928	5 layers of APPW
A3	48,818	781,088	5 layers of APPW
A4	2,613	41,808	Unrepaired sample
B1	23,344	373,504	4 layers of APPW, stainless clamp
B2	12,276	196,416	9 layers of APPW
B3	20,444	327,104	9 layers of APPW
B4	914	14,624	Unrepaired sample

Note
(1) Refer to *Interpretation of Fatigue Data* in this report for additional information on calculation of these values.

Table 5 Location of failures in the test samples

Sample Number	Orientation of cracks	Position of crack
A1	Longitudinal	1.5-in off gouge centerline
A2	Longitudinal	2.0-in off gouge centerline
A3	Longitudinal	3.0-in off gouge centerline
A4	Longitudinal	gouge centerline
B1	Longitudinal	3.5-in off gouge centerline
B2	Longitudinal	gouge centerline
B3	Longitudinal	gouge centerline
B4	Longitudinal	gouge centerline

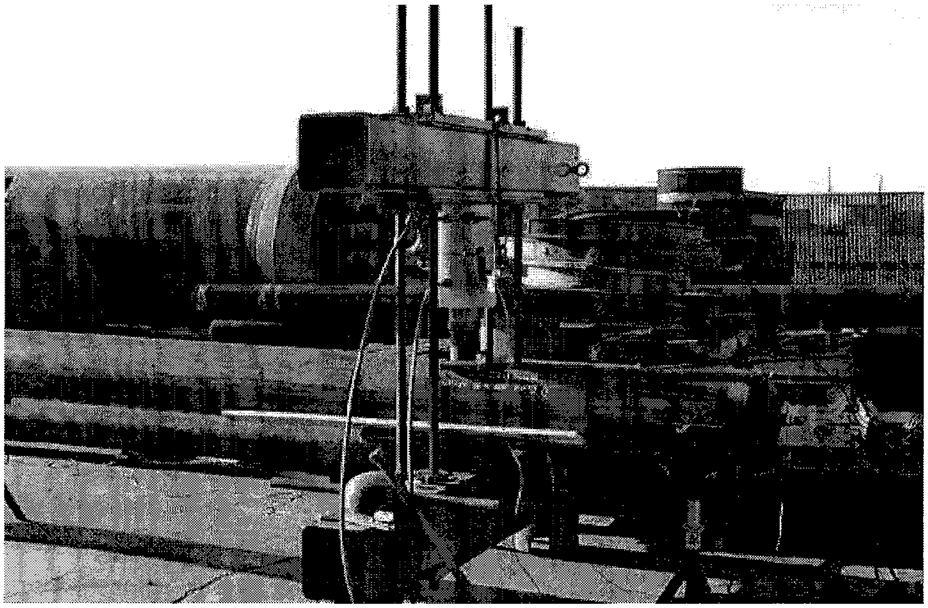

Figure 1 Dent installation rig used to install dents

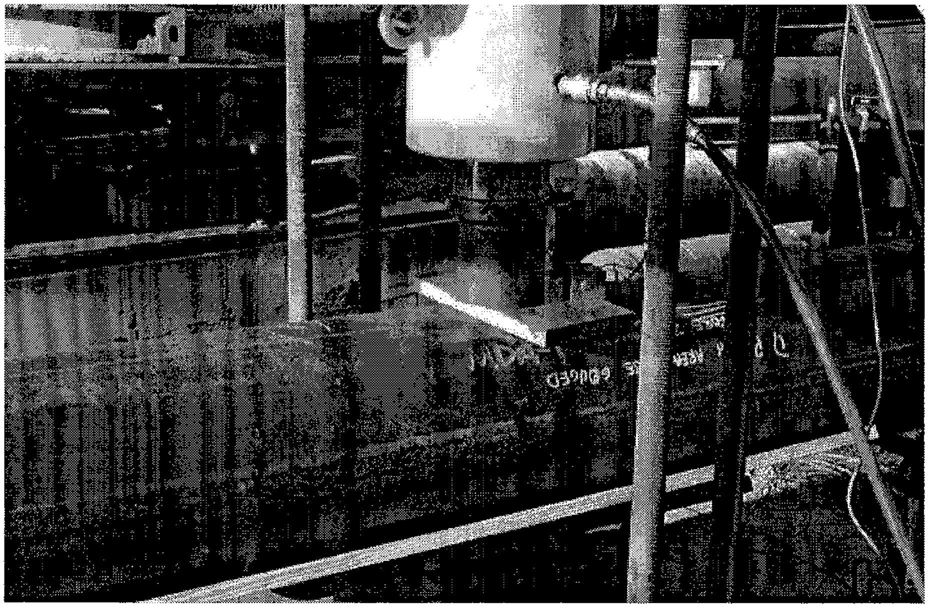

Figure 2 Close-up view of indenter plate creating dent in pipe