REPAIR OF DENTS CONTAINING MINOR SCRATCHES

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SUMMARY

In an effort to develop a method for repairing minor scratches in dents, PRC International funded an experimental research program to study repair by grinding. The results of the work showed that the repair of pipeline dents containing minor scratches, gouges, and associated cracking by means of merely grinding away the metal affected by the gouging and cracking is viable and can be done safely within certain limitations. Most importantly, the amount of metal that can safely be removed is limited by the need to retain a minimum pressure carrying capacity at least equal to 100 percent of SMYS (specified minimum yield strength). This means that grinding away as much as 20 percent of the wall thickness, regardless of the length of the anomaly, can be done safely as long as all of the cracked or damaged material is removed by that amount of grinding. Grinding away as much as 40 percent of the wall thickness is acceptable for short gouges as long as the length is limited to the amount defined by a criterion presented in the body of the report. These limits were validated by extensive testing. In burst tests of repaired and unrepaired "twin" specimens, the removal of a proper amount of damaged metal by grinding permitted the repaired specimens to survive pressurization to levels exceeding 100 percent of SMYS. In contrast, many of the unrepaired specimens exhibited failure pressures below 100 percent of SMYS, some as low as 51 percent of SMYS. In fatigue (pressure cycle) tests the repaired specimens consistently survived larger numbers of cycles than their unrepaired twins. From these findings it is concluded that the concept of removing damaged metal by grinding constitutes an acceptable repair method for dents containing minor scratches, gouges, and associated cracking. Guidelines for making such repairs in a safe manner are provided in this paper.

INTRODUCTION

This paper presents the results of a 3-year effort to develop guidelines for repairing dents containing minor scratches. The primary aim of the project was to demonstrate the feasibility of repairing a shallow gouge in a dent in a pipeline solely by means of grinding out the gouge and associated cracking. The amount of grinding to be permitted is limited to the extent that the reduced wall thickness after grinding must be adequate to maintain satisfactory pressure carrying capacity. In terms of existing industry practices this can be interpreted to mean 100 percent of SMYS (the specified minimum yield strength of the pipe material). The basis of this project was the hypothesis that any rerounding of a dent that might occur after the removal of the gouge and any associated cracking would not seriously reduce the burst pressure of the pipe, nor would it significantly affect the fatigue resistance of the pipe.

The method chosen to test the hypothesis involved testing pairs of initially-identical full-scale pipe specimens. One of each pair was to be tested in the unrepaired condition. The other was to be tested after removal by grinding of sufficient metal to eliminate the gouge and associated cracking. To compare the effects of the repair versus no-repair on serviceability, some pairs of the specimens were subjected to burst testing while others were subjected to cyclic-pressure fatigue tests. The results of the project are presented and discussed herein.

BACKGROUND

The use of grinding as a repair method is not new. Throughout the 60-year history of the API 5L Specifications, line pipe manufacturers have been permitted to remove non-indented imperfections by grinding so long as the wall thickness remaining after grinding is equal to or greater than the minimum wall thickness permitted by the applicable under-thickness tolerance limit (12.5 percent of the nominal wall thickness in many cases). In addition, various pipeline design codes permit the removal of imperfections from operating pipelines within certain limitations:

- ASME B31.8 permits repair of non-indented imperfections by grinding on in-service pipe within the same limits as the API Specification permits for new pipe.
- ASME B31.4 permits repair of non-indented imperfections by grinding so long as the amount of remaining metal passes the ASME B31G criterion.
- British Gas Standard P11 permits grinding to remove cracking or spalling (mechanical damage) to a depth of 40 percent of the nominal wall thickness in pipelines which operate at 30 percent SMYS or less and to 20 percent of the nominal wall thickness in pipelines that operate at higher stress levels. The absolute minimum wall thickness is limited to 0.16 inch. If the cracking is the result of rerounding of a gouged dent, removal by grinding of 20 to 30 mils of additional wall thickness after the crack disappears is required. No restriction is placed on this method in terms of degree of indentation, but for pipelines which operated at stress levels above 30 percent of SMYS the pressure level during the repair must not exceed 30 percent of SMYS or 85 percent of the level which the damage is known to have experienced, whichever is lower.
- The Canadian Standard CSA Z662-96 permits grinding to a depth of 40 percent of the nominal wall thickness so long as the length of the ground area does not exceed L where

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

where: a is the maximum depth of grinding
D is the outside diameter of the pipe
t is the nominal wall thickness.

Note that this is similar to the B31G limit except that it is slightly more conservative because the 0.11 in the above equation is 0.15 in the B31G equation. Grinding within the above limit can be applied to gouges in dents in the body of the pipe so long as the depth of the dent does not exceed 6 percent of the pipe's diameter. If the dent involves a weld the depth of the dent is restricted to ¼-inch.

Basis of the Experimental Efforts

The premise underlying this project is that gouged and dented pressurized pipe can be repaired solely by removing damaged material while leaving enough undamaged material to assure adequate serviceability. The idea received initial support from earlier tests conducted by British Gas[1] and Stress Engineering Services, Inc.[2] The apparent benefit that accrues from this type of repair arises from its potential to change the normally-observed behavior of gouges and dents. The deleterious effects of the latter are well known, having been demonstrated by various researchers[1-5] and by experience[4] (mechanical damage is a major cause of pipeline service failures). The gouge portion of a gouge and dent can consist of galled, crushed, moved, or removed metal. The effect of such damage usually extends beyond its visually observable dimensions. Whereas, such a defect by itself might have a predicably deleterious effect on the pressure-carrying capacity of the pipe, an accompanying dent will greatly magnify the effect. The magnifying effect is embodied in the amplified radial deformation (rerounding) that accompanies an increase in pressure and/or the amplified strain range associated with changes in pressure. Either one of these or both can produce crack extension from the gouge-damaged metal to the point where a service failure at a normal level of operating pressure results. The proposed repair method appears to have the potential to change significantly the above-described behavior. To be effective, it must accomplish removal of the damaged material such that the remaining material can withstand not only normal service stresses but the amplified strains associated with future dent movement. The potential for success in this respect seems high because of the well-known fact that "smooth" dents do not seriously affect pressure carrying capacity.[3] It is also obvious that the amount of metal removal must be limited so as to not adversely affect serviceability.

The validity of the proposed repair method can be demonstrated as follows. If it can be shown that when applied to injurious defects (i.e., known to be capable of causing failures at or near normal operating pressures) the consistent result is the ability of the "repaired" defect to survive a hoop stress level in excess of SMYS or a large number of significant pressure cycles. These requirements for validation suggested the development of an appropriate reproducible mechanical damage defect and the testing of pairs of damaged specimens, in which one (the unrepaired twin) could be shown by a test to be a significantly injurious defect (i.e., a low failure stress or a short pressure-cycle life) while the other (the repaired twin) could be shown to have a high failure pressure (> 100 percent SMYS) or a satisfactorily long pressure-cycle life. The challenge was to consistently produce enough such pairs involving a satisfactory range of pipe geometries and properties to provide confidence in the validity of the method.

The experimental needs were met by means of preliminary tests and by learning from initial tests and in some cases, mistakes. Along the way improvements in the technique evolved, sometimes through ancillary tests. In the final analysis the validity of the method is demonstrated by the results of numerous burst tests and fatigue tests of pressurized pipe specimens.

DEVELOPMENT OF A TEST METHOD

An important aspect of this project was the development of a reproducible mechanical damage defect and method to accomplish the mission of repair. Creating actual damage by means of a backhoe seemed neither feasible nor necessary. While damage-creating machinery was available, it would have been costly to use, and it would reduced our ability to obtain consistent results in significant numbers. In our view actual damage creation was not necessary, because early experiments[4] on other PRC-sponsored projects had demonstrated satisfactorily the ability to simulate the effect of mechanical damage on the pressure-carrying capacity of a pipe specimen. In particular, the concept of indenting a previously-longitudinally-notched pipe by means of a long, round-bar indenter, which was developed at Battelle,[3-5] seemed to be a viable approach. In the prior work at Battelle the indentation was done with no pressure in the pipe, but as pressure was applied to an indented specimen, ductile crack extension was produced as the dent rerounded steadily with increasing pressure. Failures were observed to occur at pressures well within the operating pressure range of the pipe. It is our belief that the ductile crack extension with rerounding adequately simulates the behavior of real mechanical damage defects. As proof we offer the evidence that the crack extension is virtually identical to that observed with real mechanical damage after the crack has extended beyond the cold-worked contact zone and the fact that such crack growth in the simulated damage specimens results in the same type of low stress failure behavior. It can be reasonably argued that once ductile crack growth extends beyond the damaged microstructure in the case of real damage, the net result is a defect no different from that produced by the damage-simulation method.

In a departure from the Battelle method in which the indentation was done at zero pressure, we elected to induce the dents with the previously notched specimen pressured to a significant level (60 percent SMYS in most cases).

Notch and Indentation Procedures

The procedure for creating damage-simulating defects began with the machining of a longitudinally-oriented V-shaped notch into an unpressurized pipe. The typical notch geometry is illustrated in **Figure 1**. The notch depths, *a*, ranged from 5 to 15 percent of the wall thickness, *t*, of the pipe (characterized by the a/t ratio). The notch lengths, *L*, varied from as short as 2 inches to as long as 10 inches, and the quantity *L* throughout this report refers to the length of the uniform-depth portion of the notch. The curved gouge-profile ends resulting from the use of a circular cutter were each less than ½ inch and were neglected in characterizing the lengths of notches. Neglecting this portion of the defect would be expected to have little or no effect in the cases of 6 to 10-inch-long notches. It probably would have an effect in the cases of 2 to 3-inch- long notches, but we only used a few of the latter for special purposes.

Next a "round-bar" indenter was placed directly over the machined notch with its long axis parallel to the axis of the notch and the pipe. At this stage each pipe specimen was already fabricated as an end-capped pressure vessel. The typical indenter set-up is shown in **Figure 2**. A saddle support with a radius larger than that of the pipe specimen was used to hold each specimen during indentation. With the specimen pressurized, usually to a level of 60 percent of the specified minimum yield strength (SMYS) of the pipe, the indenter was pushed radially into the specimen to a predetermined indentation, *d*, 5 to 20 percent of the pipe's diameter, *D*. Each dent was characterized by its d/D ratio, but in every case the final dent depth after release of the ram load was much less than its initial depth as the result of rerounding of the dent.

Over the course of the project four different indenter shapes and sizes were used. These are shown in **Figure 3**. The shapes and sizes were varied in an attempt to minimize the non-uniformity of dent depth (especially on the ends) upon rerounding. The typical indentation and rerounding shapes are illustrated in **Figure 4**. Upon release of the ram load the central portion of each dent tended to reround more than the two ends. This phenomenon arises from the fact that the curvatures in the longitudinal plane induced at the ends of the dent constitute localized restraints against rerounding, whereas, much less restraint exists at center of the dent. In every case, even when a very-large-end-radius indenter was used, the ends of the dents were characterized by "dimples". As will be shown, these dimples had essentially no effect on the static pressure-carrying capacity of the damaged pipe, but they did exhibit an influence on fatigue resistance.

Another variation in the defects was the intentional offsetting of the dent relative to the notch along the pipe axis as shown in **Figure 5**. Most of the tests were conducted with the notch centered within the dent as shown in **Figure 5a**, but some of the earlier tests were conducted with specimens in which the dent was offset as shown in **Figure 5b**. As will be shown the offsetting seemed to make no difference with respect to static pressure-carrying capacity, but it did have an effect on fatigue resistance.

The sequence of steps which resulted in the production of specimens for burst and fatigue tests is as follows.

Step 1. Machine the notch, specimen unpressurized
Step 2. Fabricate specimen with end caps
Step 3. Pressurize water-filled specimen to 60 percent SMYS
Step 4. Indent to predetermined depth bleeding water to keep pressure constant
Step 5. Withdraw indenter, initially allowing pressure in specimen to drop as ram load is released and dent begins to reround.
Step 6. Apply dye penetrant to notch region of specimens which are to be repaired
Step 7. Repressurize specimen to 60 percent SMYS an hold for one minute to achieve rerounding consistent with initial pressure upon indentation.
Step 8. Depressurize specimen to zero
Step 9. Measure residual dent depth along axis
Step 10. Grind away notch if specimen is to be repaired
Step 11. Measure remaining wall thickness in repaired area, if repaired
Step 12. Repressurize specimen to 65 percent SMYS
Step 13. Depressurize specimen to zero
Step 14. Measure residual dent depth
Step 15. Conduct either burst test or fatigue test.

In most cases these steps were followed. In a few cases certain steps were omitted, and where these omissions might have influenced the test results, the fact will be noted.

Pipe Materials

The pipe materials selected for this study are provided in **Table 1**.

System of Specimen Numbering

Except for preliminary and ancillary dent and gouge tests, the following nomenclature is used in identifying the specimens,

B1-1N

where:

B = Test-type Identifier (*B* for burst and *F* for fatigue)
1 = Material number (1 of the 9 described above)
1 = Specimen Number
N = Gouge Repair Status (*N* for not ground, *G* for ground, or *D* for dent with no gouge).

Preliminary Dent Tests

To assess the indenting technique several practice dents were made. Preliminary testing was also done to address the crack propagation at the base of a gouge for given dent depths. For brevity, results of these tests are not provided, but interested readers are encouraged to consult the PRCI Final Report on this project by Kiefner and Alexander.[7]

BURST TESTING

The primary objective of the burst testing was to determine whether the removal of gouge-damaged material by grinding restores adequate pressure-carrying capacity to gouged and dented pipe. This objective, it was felt, could best be met by bursting pairs of specimens that were damaged identically. In these pairs one would be tested as-damaged and the other would be tested after the gouge-damaged material had been removed by grinding.

Burst testing of the samples was conducted by hydrostatically increasing the internal pressure in the specimen until failure occurred. Pressure was monitored by means of a pressure transducer and the pressure level at failure was recorded. The rate of pressurization did not exceed 50 psi/minute. Pre-test and post-test measurements were made of the circumference at two locations to determine the amount of plastic strain, if any, that had occurred during the test.

The results of the burst tests are summarized in **Table 3** including the specimen numbers, the diameters, the nominal and actual wall thicknesses, the grades, and the dent and gouge parameters. Additional information includes maximum rerounding pressures, ultrasonic thickness measurements of ground-out areas, residual dent depths after rerounding, the burst pressures, the failure modes, and the amount of permanent expansion.

Since the key objective is to compare the behaviors of repaired versus unrepaired specimens, it is useful to consider the results in pairs of repaired and unrepaired specimens where possible.

Burst Test Group 1

The first nine specimens listed in **Table 3** can conveniently be described as a group because they were used to establish a "learning curve". All nine were fabricated from Material 1, a 12.75-inch OD by 0.188-inch w.t. Grade X52 ERW line pipe material with an equivalent full-size Charpy V-notch upper shelf energy of 51 ft lb. Eight of the nine specimens involved 12-inch-long notches with a/t ratios of 5 or 10 percent arranged in the offset position with respect to their dents (see **Figure 5**). One of the specimens, B1-5D involved a 5 percent plain dent (d/D = 5 percent) with no notch. All nine specimens, including the plain dent specimen were indented with the 12-inch-long, narrow indenter (designated as the 12N indenter in **Figure 3)** while pressurized to 920 psig (60 percent SMYS).

Burst Test Group 2

The next group of 16 tests is comprised of Specimens B1-10G through B6-23N in **Table 3** and Specimens B7-37G and B7-38N. This group is comprised entirely of pairs of specimens in which one is repaired and one is unrepaired.

Within this group of pairs of tests, with one exception, 6-inch long 5 percent a/t notches were used centered within dents made with the 12N indenter. The exception was the pair involving B1-10G and B1-11N. In each of these tests a 12-inch-long notch, offset 2 inches from the dent as shown in **Figure 5**, was used. The results are summarized in **Table 2**.

These pairs of results with one exception (Set 7) show a definite trend toward improvement in burst pressures after repair. All of the repaired specimens except B6-22G exhibited failure stress levels well in excess of 100 percent of SMYS. In contrast, five of the eight unrepaired specimens failed at stress levels well below 100 percent of SMYS. It is noted that in the repaired specimens in the first six sets and the eighth set, all of the damaged material was removed by grinding while the remaining thicknesses after grinding ranged from 83 to 94 percent of the original actual thickness. In the seventh set the actual thickness after repair was 70 percent of the original actual thickness reading. This fact would appear to account for the failure of the repaired specimen at a level of only 90 percent SMYS.

Burst Test Group 3

The third group of tests in **Table 3** with common characteristics involves Specimens B5-24G through B5-28N. These five tests were carried out on Material 5, a 24 inch OD by 0.250-inch wall thickness Grade X52 material. The notch used in every case was 6-inches long, and it was centered within the 12N dent (see **Figure 5**). The indenter geometry turned out to be inappropriate for this material. The rerounding of this dent tended to be extremely nonuniform; this material retained the dimpled portions of the dent to a much greater extent than the thinner, small diameter pipe.

Burst Test Group 4

Four tests are grouped together as Group 4 because of a procedural error in the first two which necessitated repeating them. All four were carried out on Material 4 which was 12.75-inch OD by 0.225-inch wall thickness X65 material. This material, it is recalled, was relatively tough, exhibiting a full-size equivalent Charpy V-notch upper shelf energy of 90 ft. lb. It is also recalled that the previous test involving an unrepaired notch and dent in this material, B4-19N, failed at a relatively high level (113 percent SMYS). With this result and the result of the test of the repaired "twin", B4-18G being a failure at 125 percent SMYS, the benefit of the repair was not proven to be very significant. So, one purpose of the first two Group 4 tests was to test a pair of specimens in which, it was hoped, a lower "unrepaired" failure stress level would be obtained. To accomplish this an initial notch with $a/t =$ 10 percent was machined into each specimen. In comparison the notches in Specimens B4-19N and B4-18G had depths of only 5 percent of the wall thickness. The initial dent size ($d/D = 15$ percent) was the same.

The inability to interpret the results of Specimens B4-29N and B4-30G left us no choice but to repeat the tests. So Specimens B4-29NR and B4-30GR were prepared and tested with target parameters identical to those of B4-29N and B4-30G. The results of these test were:

Failure of B4-29NR (unrepaired) at 2342 psig (102 percent SMYS)
Failure of B4-30GR (repaired) at 2544 psig (111 percent SMYS)

It was noted that the repair of B4-30GR required grinding to a remaining wall thickness of 72 percent of the original wall thickness over the entire notch length (6 inches), so its failure of 111 percent SMYS is understandable. But, the result still demonstrates an effective repair. The grinding was done carefully with periodic checking to make sure that additional grinding was still necessary. If the unrepaired twin, B4-29NR, underwent the same amount of crack growth upon rerounding to the 1376 psig (60 percent SMYS) level, the resulting failure at 102 percent SMYS suggests that high toughness materials may be inherently more resistant to damage than low toughness materials. Logically, this is what one might expect.

Burst Test Group 5

Group 5 tests consisted of only one pair of specimens, B8-36N, unrepaired, and its repaired twin, B8-35G. What makes this pair unique is the manner in which the unrepaired specimen behaved. Like Material 4, Material 8 is a modern high-toughness material being 24-inch OD by 0.250-inch wall thickness X65 with a full-size equivalent Charpy V-notch upper shelf energy of 88 ft. lb. Unlike Material 4, however, it exhibited a "separation" during the testing of the unrepaired specimen which grossly changed the expected outcome. Both specimens were fabricated with 11-inch long notches rather than the 6-inch notches used in the 12.75-inch OD pipes and the previously tested 24-inch OD pipes. The longer notch is reasonable in keeping with the fact that the "Folias" stress concentrating effect of a longitudinal flaw is a function of $L/\sqrt{Dt}$, and such a notch if used in the previous 24-inch test might have given better results. More importantly, however, the longer (24-inch) 24N indenter was used to move the dimples at the ends farther away from the notch. The notch depth in both specimens was 10 percent of the wall thickness and the d/D ratio of the dents in both was 15 percent. Denting was carried out at 812 psig (60 percent SMYS). The repair of B8-35G required grinding to an average remaining wall thickness of 77 percent of the actual original value. Again as in the case of the repair of B4-30GR, the grinding was done carefully in small stages to be sure no more was done than necessary to make the crack disappear.

Upon being pressurized to failure the repaired specimen, B8-35G, failed at 1625 psig (120 percent SMYS), demonstrating an entirely acceptable level for a repaired specimen. The unrepaired specimen, B8-36N, on the other hand, failed at a pressure level of 1871 psig (138 percent SMYS) after nearly 3 percent circumferential expansion.

The outcome of the test of Specimen B8-36N caused concern at first, until the nature of the rupture was examined, revealing that ductile tearing had taken place at the root of the notch. At some stage of pressurization a "separation" formed, interrupting the tearing through the wall thickness and causing the specimen to behave essentially as an unnotched specimen with at least 70 percent of the original wall thickness of the pipe. The formation of a separation is not unexpected in a controlled-rolled material, but since one cannot depend on them, it is not safe to say that damage in such a material does not have to be repaired. The notch certainly had produced tearing upon rerounding and it is reasonable to believe that, had the separation not occurred, the failure of B8-36N would have occurred at a significantly lower pressure level.

Burst Test Group 6

These four tests were carried out to validate the repair-by-grinding hypothesis for cases involving deep grinding (to a maximum of 40 percent of the wall thickness). Such grinding is permitted in a gouged and dented area by CSA Z662 in Canada provided that the remaining wall thickness is at least 60 percent of the nominal value required for the pipeline's maximum operating pressure and that the overall dimensions of the removed metal (axial length and maximum depth) fall within the limits of a criterion similar to the ASME B31G criterion. That is the length L must be:

$$L < 1.12\ B\ \sqrt{Dt}$$

where B is

$$\sqrt{\left(\frac{\frac{a}{t}}{1.1\frac{a}{t} - 0.11}\right)^2 - 1}$$

and $a/t \le 0.4$. The only difference between this criterion and ASME B31G is the constant 0.11. In the ASME B31G criterion this value is 0.15. The CSA criterion is slightly more conservative than B31G because of this.

The materials selected for these tests were Material 7 and Material 5. Material 7 is 12.75-inch OD by 0.188-inch wall thickness X52 material. To meet the above dimensional limitations, an area of grinding with a maximum depth of 40 percent of the wall thickness would be limited to 1.19-inches in length. Material 5 is a 24-inch OD by 0.250-inch X52 material. The length limitation for a ground area with a maximum $a/t = 0.4$ in this material would be about 1.89-inches. The biggest challenge in creating the specimens for these tests was determining how deep to make a notch and dent so as to end up with an area that would require no more the 40 percent thickness removal to eliminate the crack. This was done through a series of ancillary tests described later in the report. The results of the ancillary tests suggested that the initial notches should be 18 percent of the wall thickness and that the initial dents should be 10 percent of the pipe's diameter for both materials. On the assumption that the CSA criterion could be expected to give conservative predictions of remaining strength, we decided to make the notches somewhat longer than the maximum values calculated above. The length of the notch for Material 7 was set at 2 inches and the 12N indenter was used to make the dent. For Material 5 a notch length of

5 inches was selected and the 24N indenter was used. All four specimens were indented while pressurized to levels corresponding to 60 percent SMYS.

Specimen B7-31G was repaired by grinding to an average remaining thickness of 62 percent of the original thickness over the 2-inch length of the notched area. When pressurized to failure the specimen ruptured at a pressure level of 1716 psig (112 percent SMYS). The companion unrepaired specimen, B7-32N, in contrast, failed as a leak at a pressure level of 974 psig (64 percent SMYS). Specimen B5-33G was repaired by grinding to an average remaining thickness of 61 percent of the original thickness over the 5-inch length of the notched area. When pressurized to failure, the specimen ruptured at a pressure level of 1276 psig (118 percent SMYS). Its companion unrepaired specimen B5-34N ruptured at 902 psig (83 percent SMYS). These results provide confirmation that the repair hypothesis extends to defects requiring grinding away up to as much as 40 percent of the wall thickness.

Burst Test Group 7

These two experiments were the last two conducted in the program, and they involved the largest-diameter pipe material. Material 9 is a 32-inch OD by 0.281-inch wall thickness X52 material with a full-size equivalent Charpy V-notch upper shelf energy level of 40 ft.-lb. Each specimen was fabricated with a 10-inch-long notch with an a/t of 10 percent. Each was indented with the 24N indenter to an initial depth of 10 percent of the pipe's diameter. After its dent was made at a pressure level of 548 psig (60 percent of SMYS) and its internal pressure dropped upon relaxation of the indenting load, Specimen B9-40N was repressurized in the same manner as other specimens to restore the pressure to 548 psig to achieve the realistic amount of rerounding. In the process the specimen ruptured when the pressure level reached 484 psig (53 percent of SMYS). As a result of this situation the twin specimen, B9-39G, was indented at 548 psig, but the repressurization to produce rerounding was carried out to a level of only 400 psig (44 percent of SMYS). Specimen B9-39G survived this repressurization and was depressurized for repairing. Upon grinding we were unable to remove the "crack" until we had ground excessively deep. We decided that it would not be appropriate to test the specimen because we were still seeing indications of a crack after removing more than 50 percent of the wall thickness. Therefore, this pair of tests did not produce a useful result. It is our feeling that the initial dent size chosen is inappropriately severe for this pipe. Apparently, a dent which could realistically survive in this pipe cannot be made in the manner that our experimental dents were made.

Conclusions from the Burst Tests

The burst tests of unrepaired and repaired specimens were intended to show that serious gouge and dent defects (i.e., those which would fail at the operating stress level of a pipeline) could be repaired by merely grinding away the gouge-damaged material to an extent that they would have failure stress levels above 100 percent of SMYS after being repaired. This implies that the amount of grinding must achieve the desired repair without reducing the wall thickness to the point that it would be insufficient to support the 100 percent of SMYS level. The hypothesis was based on the assumptions that gouges cause failures by extending cracks deeply into the remaining wall thickness as the dent rerounds under increasing internal pressure and that if the gouge damaged material is removed, such crack growth cannot take place and the dent will reround without causing a failure. The validity of the hypothesis was demonstrated by the previously described tests and the data plotted in **Figure 6**.

Figure 6 presents the results of 20 "unrepaired" notch and dent tests. This figure shows that 10 of the 20 exhibited failure stress levels below 100 percent of SMYS, ranging from 51 to 100 percent of SMYS. In contrast, as also shown in **Figure 6** all of the "repaired" specimens, except those which were ground too deeply, failed at stress levels exceeding 100 percent of SMYS. In addition, as noted in the discussions of the individual tests, each repaired specimen failed at a higher stress level than its unrepaired twin except in the case of one pair in which the repaired specimen was ground too deeply and one pair in which the unrepaired specimen's behavior was influenced by a "separation". Because these tests have involved pipe diameters ranging from 12:75-inch to 24-inch, wall thicknesses ranging from 0.188-inch to 0.250-inch and grades ranging from X52 to X65, it is reasonable to believe that the method of repair by grinding the gouge-damaged material out of a dent is a valid means of restoring adequate stress carrying capacity to a damaged pipe. It is also important to note that the results have validated the procedure permitted by CSA Z662, namely grinding to depths of 40 percent of the original wall thickness provided that the length of the ground area is limited as described in that document.

FATIGUE TESTING

The primary aim of the fatigue tests using cyclic internal pressure variations, was to quantify the degree of benefit derived from repair by grinding by comparing of the fatigue lives of repaired and unrepaired specimens. One would expect the fatigue lives of the repaired specimens to be significantly longer than those of the unrepaired specimens.

Development of the Fatigue Test Matrix

As with the burst tests, a fatigue testing matrix was developed in order to meet the research objectives. The fatigue tests were carried out on the same family of 12-inch OD pipe materials as that used in the burst tests. The specimen numbering system is as explained in conjunction with the burst tests. The selection of the defects used in the fatigue testing is based upon results from the burst tests. For example, the high burst pressure for the 5 percent dents and 5 percent gouges indicated that a defect of this size would be of little use in fatigue testing, so most of the fatigue tests were carried out with 10 percent or 15 percent dents. The fabrication procedure used in preparing the fatigue samples was the same 15-step procedure as that used for the burst tests.

Fatigue Testing Experimental Procedures

In conducting the fatigue tests, cyclic internal pressures were applied to the pipes with the pressure range based on a percentage of SMYS. Water was used as the testing medium.

The selection of the pressure range was based on previous research[2] which involved samples with reasonable pressure variations, but at the same time had sufficient amplitudes to induce failures within 50,000 cycles. Based on these requirements, the following pressures were applied:

1. 25,000 cycles (or until failure) with ΔP = 36% - 72% SMYS
2. 25,000 cycles (or until failure) with ΔP = 7% - 78% SMYS (double the above pressure range but with minimum pressure of 100 psig)

This selection of pressures was well-suited for the given defects when it is considered that all samples failed before 50,000 cycles were reached. An additional benefit in selecting pressure variations based on percentages of SMYS is that direct comparison of results from pipe samples with different pipe geometries (D/t) and defect characteristics (gouge and dent depths) can be made. The mathematical method used to determine an equivalent number of cycles for samples cycled with different pressure differentials is explained below.

The equivalent number of cycles is used to normalize the data so that the cumulative damage imposed by the multiple pressure cycles (two in these tests) can be incorporated into one value. The Equivalent Number of Cycles is calculated using an equation based on a combination of Miner's Rule and the DOE-B curve. This method calculates an equivalent number of cycles at a specified pressure for a pipe which was pressure cycled at other pressure ratios. This equation is presented below.

$$N_{B_{eq}} = N_{B_1}\left(\frac{\Delta P}{\Delta P_{B_1}}\right)^{-4} + N_{B_2}\left(\frac{\Delta P}{\Delta P_{B_2}}\right)^{-4}$$

where:

N_{Beq} = Equivalent number of cycles for Sample B at the specified pressure differential, ΔP
ΔP = Base pressure differential
N_{B1} = Number of cycles obtained for Sample B at ΔP_{B1}
ΔP_{B1} = First pressure differential for Sample B
N_{B2} = Number of cycles obtained for Sample B at ΔP_{B2}
ΔP_{B2} = First pressure differential for Sample B

Fatigue Test Results

The results of the fatigue tests are summarized in **Table 4** including the specimen numbers, the diameters, the nominal and actual wall thicknesses, the grades, and the dent and gouge parameters. Additional information includes maximum rerounding pressures, ultrasonic thickness measurements of ground-out areas, numbers of cycles to failure of relevant ranges including total equivalent cycles, mode of failure and location of failure.

Since the objective is to compare fatigue lives of repaired versus unrepaired specimens, it is useful to consider, as we did with the bursts test, the results in pairs of repaired and unrepaired specimens where possible. Defects F2-1N and F2-2G which were located in a single specimen of Material 2 (12.75-inch OD by 0188-inch wall thickness X52) were not subjected to pressure cycles because defect F2-2G failed after it was ground too deeply. It failed upon rerounding. Subsequently, the following tests were completed successfully.

Fatigue Test Group 1 (F2-3G, F2-4N, F2-5G, F2-6N)

These four tests were carried out on samples of Material 2 (12.75-inch OD by 0.188-inch wall thickness X52, 39 ft.lb. CVN). All four notches were of the 12-inch offset type shown in **Figure 5**. All dents were made with the 12N indenter shown in **Figure 3**. As in the case of the burst tests, the denting was done with the specimens pressurized. Final dent depths before grinding were achieved by pressurizing to 996 psig (65 percent SMYS). The defect parameters of these specimens are shown in **Table 5**..

The specimens were subjected to cycles of internal pressure as described previously. Each test was terminated when a fatigue crack grew through the wall thickness causing a leak. The results of the tests on these four specimens listed by pairs of identical specimens are provided in **Table 6**.

Before one can adequately judge the meaning of the results, it is necessary to examine the nature of the failures. First, it is noted that all were leaks and all of the leaks were located in or near one of the two "dimples". Both leaks were located to one side of the deepest part of the dimple, the side toward the center of the dent.

The results of the first group of tests suggest that the repair hypothesis is valid, namely, that repair by grinding enhances the fatigue life of a gouged and dented pipe. It is worth noting that the lives of the repaired specimens were probably foreshortened by the fact that the grinding was done in a manner that left fairly deep grind marks in a longitudinal orientation. If these areas had been ground circumferentially to a smoother finish, it is probable that they would have exhibited longer lives.

Fatigue Test Group 2 (F2-7G, F2-8N)

The results of tests of these two specimens are considered together but separately from the others because the dents in these specimens were unique. They were the only dents made with the "modified" indenter (see **Figure 3**). This indenter produced relatively short dents with dimples separated by only about 3½ inches. The notches in both specimens extended clear through and beyond the dimples. Specimen F2-7G (repaired) failed after 170,637 equivalent cycles exhibiting the longest fatigue life of any of the pressure-cycled specimens. Specimen F2-8N (unrepaired) failed after 18,093 cycles exhibiting a life only about 1/10 that of its repaired twin.

The leaking areas of both specimens were exposed by breaking them after cooling in liquid nitrogen. Both leaks were centered on the dimples in these dents unlike those of the Group 1 defects. In the cases of Specimens F2-7G and F2-8N the dimples seemed to be smoother and more symmetric than those of the Group 1 specimens. This may have favored the cracks propagating symmetrically within the center of the dimples.

Fatigue Test Group 3
(F2-9G, F2-10N, F2-11G, F2-12N, F3-13G, F3-14N)

These six tests are considered as a group because they were conducted on similar materials with similar dent and gouge parameters. The materials were 12.75-inch OD by 0.188-inch wall thickness X52 line pipe materials which exhibited full-size equivalent Charpy V-notch uppershelf energies of 39 ft.lb. (Material 2) and 63 ft.lb. (Material 3). Each had a 6-inch-long 5 percent through the wall notch, and each was initially indented to a depth of 10 percent of the pipe's diameter with the 12N indenter. In these specimens the notches did not extend into the dimpled areas.

The fracture surfaces of the unrepaired specimens (F2-10N, F2-12N, and F3-14N) were examined and in each case the failure resulted from a fatigue crack growing from the notch or the initial ductile tear that resulted from rerounding. In these cases the fatigue lives appeared not to have been influenced by the dimples because the notches did not extend into the dimpled regions. In the cases of the first two specimens (F2-10N and F2-12G), the failures occurred as ruptures after the cracks had grown about half way through the wall thickness. In the case of Specimen F3-124N the cracks were all of the way through the wall thickness and the mode of failure was that of a leak.

The results of the Group 6 tests further confirm the repair hypothesis that grinding out the damaged material can be expected to improve fatigue life. The ratios of repaired to unrepaired lives were 4.4 for the F2-9G, F2-10N pair, 6.2 for the F2-11G, F2-12N pair and 1.7 for the F3-13G, F2-14N pair. The actual benefits of the repairs may be higher than these ratios indicate because the dimples undoubtedly foreshortened the lives of the repaired specimens.

Fatigue Test Group 4 (F4-15G, F4-16N)

These two tests were the only fatigue tests involving Material 4, the 12.75-inch OD by 0225-inch wall thickness X65 material with 90 ft.lb. full-size equivalent Charpy V-notch upper shelf energy. The specimens were fabricated with 6-inch-long, 5 percent through-the-wall notches. The specimens were indented with the 12N indenter to a depth of 15 percent while pressurized to 920 psig (43 percent of SMYS), and rerounding was completed at that pressure level as well. The specimens were subjected to cyclic pressures ranging from 550 to 1100 psig which for this material constituted a range of 24 to 48 percent of SMYS. In contrast, most of the other fatigue tests were conducted by cycling the pressure between 36 and 72 percent of SMYS. Both of these factors resulted in the cycling being conducted with relatively deep dents throughout the pressure-cycle life.

Both specimens developed leaks at locations influenced by the dimples. While the notches in these tests were 6-inches-long at the bottoms, the tapered depth portions extended their surface lengths nearly to 7 inches. In the case of F2-16N the dent was inadvertently offset about ½-inch from being centered over the notch. Compounding this circumstance was the relatively lower degree of rerounding that was applied to these specimens. As a result both ends of the notch in F4-16N, one more so than the other, were located on the sloping areas where the dimples started.

In terms of pressure-cycle lives the repaired specimen exhibited a life 1.3 times that of the unrepaired specimen. This pair of tests showed the least benefit of the repair of any of the pairs of tests. Undoubtedly, the relatively deeper dents in these two specimens influenced their behavior.

Fatigue Test Group 5

This final group of four fatigue tests was carried out on Material 6, a 12.75-inch by 0.188-inch wall thickness X52 material with 47 ft.lb. full-size equivalent Charpy V-notch upper shelf energy. The notches in these specimens were 6-inches in length and 5 percent through the wall thickness in depth. The dents were made with the 12N indenter to an initial depth of 15 percent of the pipe's diameter. The only difference between the two sets of tests was the fact that they were subjected to different test conditions. Specimens F6-17G and F6-18N, were indented and rerounded at a pressure level of 600 psig (39 percent of SMYS), and they were subjected to a pressure cycle range of 100 to 650 psig (6.5 to 42 percent of SMYS). In contrast, Specimens F6-19G and F6-20N were indented and rerounded at a pressure level of 920 psig (60 percent of SMYS) and they were subjected to a pressure cycle range of 550 to 1100 psig (36 to 72 percent of SMYS). The latter test conditions are typical of those used in the majority of the tests, whereas the former test conditions were unique to Specimens F6-17G and F6-18N. The intent of the lower pressures was to provide a case in which deeper residual dents could be evaluated using the same pressure range (500 psig). As seen in **Table 4** immediately after rerounding the residual depth of the dents in Specimens F6-17G and F6-18N were 4.6 percent of the pipe's diameter.

The results of the tests of the repaired specimens were influenced by an unintended circumstance. Part of the notch in each of the repaired specimens was not entirely removed. In both cases the repaired specimens developed leaks which initiated at these incompletely removed notches. This undoubtedly resulted in the unusually short pressure cycle lives for both specimens. Specimen F6-17G leaked after 11,427 cycles and Specimen F6-19G leaked after 11,366 cycles. In comparison, the next shortest life for a repaired specimen was that of Specimen F4-15G (19,384 cycles).

The tests of the unrepaired specimens resulted in relatively short lives, 4254 cycles for F6-18N, and 4947 cycles for F6-20N. These relatively short lives are probably related to the fact that the notches extended into areas influenced by the dimples.

Conclusion from the Fatigue Tests

Clearly, repairing a gouge by grinding to remove the damage improves fatigue life. Whether or not it extends the life to beyond the useful life of a pipeline depends on the pressure-cycle severity applied to the pipeline and the depth of the residual dent. In some of the experiments, the improved fatigue lives would certainly be longer than the useful life of a pipeline. In other cases, however, the improvements might not have prevented eventual failure in a pipeline subjected to intense pressure cycling.

ANCILLARY TESTS, MEASUREMENTS AND ANALYSES

At various times throughout the project it was necessary to conduct ancillary tests to optimize the value of the burst tests and the fatigue tests. As described early in the report, preliminary tests were conducted to establish the types of dents and notches needed to accomplish the validation of the repair hypotheses. In the following paragraphs additional types of tests measurements, and analyses are described which were useful in resolving some of the questions raised by the burst and fatigue test results.

Indenter Load Versus Indentation

Indenter load versus indentation at constant pressure was measured on eight occasions. The maximum load for the target dent depth with the 12N indenter was around 81,000 lb whereas that with the 18W indenter was about 99,000 lb. The longer, wider indenter, not surprisingly, required more load to achieve the same dent depth.

Effects of Dent and Notch Parameter Variations

In order to understand and reduce the occurrences of certain anomalous results several tests were conducted with the objectives of evaluating indenter shape effects and measuring the amounts of crack growth obtained for various initial notch and dent depths. These were known as the P1, P2, and P3 tests. All were carried out on samples of Material 7 (12.75-inch OD by 0.188-inch wall thickness X52 with a CVN value of 41 ft.lb. full-size equivalent). The results of these tests are summarized in **Table 7**.

Tests P1A, P1B, P1C, and P1D

Tests P1A, P1B, P1C, and P1D were conducted to evaluate the effect of indenter shape. Details associated these tests are provided in **Table 7**. Each test involved a 6-inch-long, 5 percent through-the-wall notch.

It is important to note that Specimen P1C survived pressurization to this level even though it had been indented to 20 percent of the pipe's diameter, whereas Specimen P1B failed at 1050 psig. The difference must be attributable to the different degree of crack growth on rerounding of the wide dent versus rerounding of the narrow dent. A simplistic strain analysis supports this hypothesis. If one assumes that upon indentation, the pipe wall thickness conforms to the curvature of the indenter, then the bending strain upon maximum indentation is given by

$$\epsilon = \frac{t}{D} + \frac{t}{2R}$$

where: t is the wall thickness of the pipe
D is the diameter of the pipe
R is the radius of the indenter

The first term comes from assuming that the pipe is first flattened under the indenter. The second term comes from the assumption that upon continued indentation beyond flattening, the pipe takes on the curvature of the indenter. So the comparison of the strains produced by the 12N and the 18W indenters in the 12.75-inch OD by 0.188-inch w.t. pipe is:

$$\epsilon_{12N} = \frac{0.188}{12.75} + \frac{0.188}{2(0.5)} = 0.203 \ (20.3\% \mathit{strain})$$

$$\epsilon_{18W} = \frac{0.188}{12.75} + \frac{0.188}{2(2)} = 0.062 \ (6.2\% \mathit{strain})$$

The strain level upon rerounding is harder to assess because the pipe does not go back to a flat profile. Nevertheless, the above comparison suggests that the indenting and rerounding with the 12N indenter provides a much more severe effect than that associated with the 18W indenter. The results of the P1 tests reflect this effect.