

A SUCCESSFUL STRATEGY FOR MANAGING THE MECHANICAL INTEGRITY OF COKE DRUMS

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ABSTRACT

A novel approach to mechanical integrity was utilized for addressing failures in an old set of coke drums. Using a rigorous routine of inspections, assessments, and long-term repairs, drums which had suffered accelerated deterioration, unpredicted cracks, and loss of containment were transformed to a reliable set of vessels. Despite old age and thin walls, due to the success of this strategy and results of a fatigue test program, plans to replace these vessels were canceled and the time between turnarounds is being considered for an increase. In this paper, we describe the approach that was used and compare results from this set of drums to another set at the same facility that was managed differently.

INTRODUCTION

The subject of this paper is two sets of coke drums used in two upgraders to process oil sand bitumen at the same site in Northern Alberta, Canada. Both sets were operated using a variable cycle time that decreased over the years.

Upgrader 1 (U1) has 8 coke drums. Six of them (5C-3, 5C4, 5C-5, 5C-6, 5C-7, and 5C-8) are made out of C-½Mo and have been in operations since 1967. These are some of the oldest in-service drums in industry with 50 years of service and over 10,000 cycles of operation. The

other two (5C-50 and 5C-51) are made out of 1Cr- ½ Mo and have been in service since 1981. All U1 drums are 26 feet (7,925 mm) in diameter, 66.5 feet (20,269 mm) Tangent-to-Tangent long, and are made from courses with variable thickness that ranges from 0.64" (16.3 mm) to 1" (25.4 mm). Design pressure is 40 to 70 psig (276 to 483 KPa) and 850 to 925 °F (454 to 496 °C) from top to bottom, respectively.

Upgrader 2 (U2) has six coke drums all of which are made out of 1Cr- ½ Mo. Four have been in operations since 2001 and two since 2007. All U2 drums are 32 feet (9,754 mm) in diameter, 91 feet (27,737 mm) Tangent-to-Tangent long, and are made from courses with variable thickness that ranges from 1.41" (35.8 mm) to 1.89" (48 mm). Therefore, U2 drums are significantly younger and thicker but slightly larger in diameter and height than U1. Design pressure is 71 psig (490 KPa) and 885 to 940 °F (474 to 504 °C) from top to bottom, respectively.

U1 drums have experienced cracks and some through wall cracks that had been increasing in frequency from 2002 to 2008. In 2008, a new approach to integrity management was adopted and a comprehensive test program was initiated. The program was so successful in controlling bulging and cracking in the shell that plans to replace these drums were cancelled and the time between turnarounds is being considered for an increase.

In this paper, we discuss the history of shell failures, the basic components of the new management strategy, the fatigue test program that was used to predict future performance, and a summary of results.

HISTORY OF SHELL FAILURES

Figure 1 is a bar chart that tracks the number and location of shell cracks in the eight drums of U1. The abscissa is the year and the ordinate is the number of cracks. The data is color-coded per drum number and through-wall cracks are identified using circles.

The chart shows that first and most recurring cracks were found in drum 5C-6. First shell crack in the unit was recorded in 1986 in the 5C-6 area later identified as “Bulge B”. In 1997, three cracks were found in the same bulge including a through-wall crack. Starting in 2001, another relatively small local bulge in the same drum, referred to as “Bulge A”, became the most problematic bulge and site of recurring through-wall cracks on a near annual basis. This small bulge which was insignificant in size and far from circumferential seam welds became a real challenge and a cause of concern regarding the ability to predict and reliability of repairing failures.

Starting twelve years after the first crack was found, since 1998, all drums have cracked and cracks were found almost on an annual basis. In addition to 5C-6, through-wall cracks were found in drums 5C-3, 5C-4, 5C-5, and 5C-50 (the younger chrome alloy drum). In some cases, steam spewed from cracks and, in one case, a flame shot from the drum to a distance of about 30 ft (9,144 mm).

The chart shows how crack numbers grew almost exponentially which is common in industry. However, this trend came to an abrupt change after 2008, the year the new mechanical integrity management approach was first implemented. The last through wall crack was found in 2008 and, in 2009, two cracks that did not go through wall were found in 5C-50 and 5C-51. Since then, this data update has been discontinued because there were no more unpredicted cracks in these drums. The chart stops at 2009 because cracks after this year were predicted by the new inspection-assessment routine.

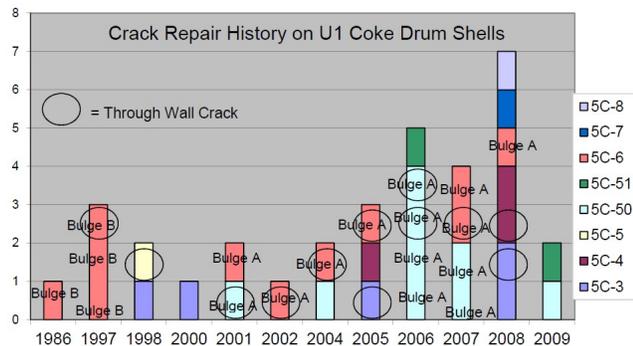


Figure 1: Crack Repair History in U1

Figures 2, 3, and 4 show examples of a leak found during quench, a through-wall crack at a bulge, and “elephant-skin” cracking in the drums, respectively.



Figure 2: A leak found during quench



Figure 3: Typical bulge and through wall crack

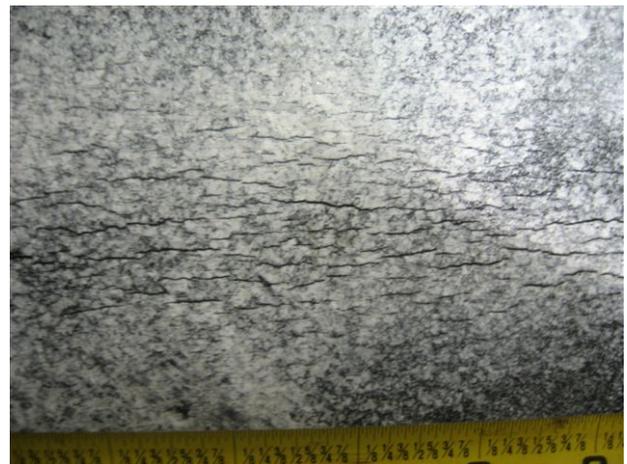


Figure 4: Typical Elephant skin cracks

MANAGEMENT STRATEGY

The core of the new integrity management strategy is the understanding that bulging and cracking in coke drums are inevitable and that with the right inspection, assessment, and repair tools, a systematic proactive integrity program can extend their economic life virtually indefinitely.

Since the new management strategy was adopted, every three years, during scheduled unit turnarounds, all or most drums receive thorough inspections followed by bulging assessment and long-term repairs of areas susceptible to bulging-induced or stress-riser cracking.

The extent and methods of inspections are a function of bulging severity and inspection history for each drum. Visual as well as nondestructive testing methods have been employed to search for and size cracks. But the core and only global inspection method consistently utilized is internal laser scanning which provides the radius measurements that are needed to perform bulging assessment. An example color-coded radius map from an internal laser scan is shown in Figure 5.

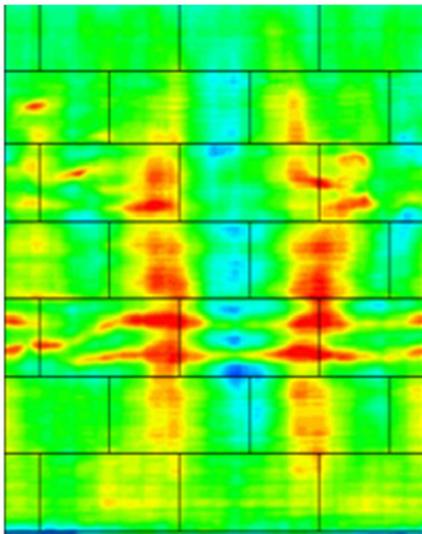


Figure 5: An example of a color-coded radius map from an internal laser scan

The assessment of bulges in coke drums was not possible per API 579/ ASME FFS-1 standard [10] and its predecessor recommended practice [11] because loads could not be defined. The randomness of channeling inside coke beds and the properties of hard coke result in highly inconsistent and unpredictable thermomechanical loading on drum shells.

Initially, to assess the condition of individual drums, the magnitude of bulging was used as an indicator of severity. After the recurring cracks in the small “Bulge A” of 5C-6 which started in 2001, it was clear that bulging magnitude was no indicator of the potential for bulging-induced cracks.

An attempt to use stress concentration factors from linear elastic finite element analysis under nominal pressure as a severity indicator was quickly abandoned after it showed that the repeatedly cracking “Bulge A” had a much lower stress concentration factor than the stable “Bulge B” which had developed no cracks for years. A recent detailed parametric study helped to explain why a bulge that results in minimal stress concentration can develop cracks while one with higher stress concentration does not. [9]

In 2004, a pattern recognition method was developed for identifying the shapes of bulges that correlated with cracks in a database of failure examples [1]. This method, which was found to correlate with and predict failure locations [2,3], was successfully utilized in the new integrity management program until 2011.

In 2011, a method that uses plastic strain as an indicator of bulging severity was developed. [4] The analysis provides a measure of severity from the ratio of calculated plastic strain to strain limit in a percentage form. To help identify and visualize locations that are susceptible to bulging-induced cracks, three-dimensional severity maps can be presented of this measure. The map of Figure 6, which was calculated from a laser scan of drum 5C-6, shows a sharp red peak that corresponds to “Bulge A” which had experienced repeated cracks over the years as well as a mild circumferential severity zone (yellow to light green) that corresponds to the stable “Bulge B”. In the three-dimensional map, the x-axis is azimuth around the circumference in degrees; y-axis is the height in inches from the bottom Tangent Line; and Z-axis is bulging severity as a percentage.

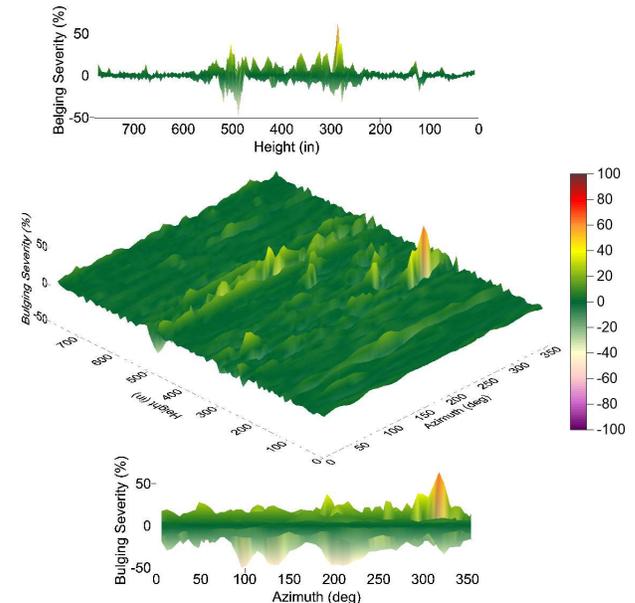


Figure 6: An example bulging severity map

Severity grade is defined as “Design”, “Concern”, “Danger”, and “Failure” levels. Positive and negative values refer to failure initiation on the inside and outside surfaces of the wall, respectively. Table 1 relates this strain-based bulging severity measure to severity grade, likelihood of bulging-induced cracks, and recommended frequency of laser scanning.

Table 1. Bulging Severity

Bulging Severity Magnitude	Severity Grade	Likelihood of Bulging-Induced Cracks	Recommended Frequency of Laser Scanning
80% to 100%	Failure	Likely	6 months to 1 year
60% to 80%	Danger	Probable	1 year
40% to 60%	Concern	Possible	1 to 2 years
0 to 40%	Design	Unlikely	2 to 3 years

While the most dominant damage mechanism in coke drums is believed to be low-cycle fatigue, this plastic strain assessment approach utilizes local failure criterion not fatigue. This approach is based on the hypothesis that crack initiation from bulging is a result of excessive local plastic deformation.

Since 2011, this strain-based technique was utilized in the integrity management program to identify and rank the areas that are most susceptible to cracking. So far, it was found to be an accurate indicator of observed bulging-induced cracks which confirmed similar findings of other operating companies [5,6]. To track historical changes in the condition of individual drums using the same measure, prior assessments were redone using this technique.

When more than one scan is analyzed for a given drum, a historical trend is established. The change in severity of particular bulges over time can be used to determine their criticality and rate of deterioration. This information helps unit managers forecast maintenance costs and plan drum repairs or replacement in a timely and cost-effective manner.

The new integrity management strategy requires that, once bulging severity reaches or is predicted to reach an unacceptable level, long-term bulge repairs be pursued in a proactive manner.

Plant experience has shown that routine crack repairs are short-lived when cracks are induced by bulging. To avoid recurrence of these cracks, industry has utilized three long-term repair methods; window replacement, can replacement, and weld overlay repair. Engineering assessment performed on these U1 drums and their bulging patterns concluded that, in this case, weld overlay repair was the most effective solution.

After severity is assessed, repair plans are developed based on strain-based bulging severity as well as the history of inspections and repairs. An engineered repair plan includes the following details:

- Weld material,
- Side of application (inside or outside surface),
- Weld thickness,

- Number of layers,
- Weld procedure, and
- Perimeter geometry and treatment detail.

Repairs have been analyzed using finite element analysis to rule out the following possibilities:

- Excessive distortions,
- Local failure, and
- Instability.

To maximize service life, various perimeter geometries were analyzed using finite element analysis and an effective profile was selected as a repair standard.

Weld overlay repairs are performed using automated welding technology, as shown in Figure 7. The computer controlled welding that is supervised by qualified operators has been utilized for structural repairs of coke drums for about 20 years. A recent comprehensive long-term repair of a set of eight drums at one site totaled more than 3,000 square feet (280 m²) of weld overlay area. [7]

In 2008, the first large band of weld overlay repair was done on drum 5C-6. Since then, all 8 drums of the U1 coker plant have been overlaid with welding bands.

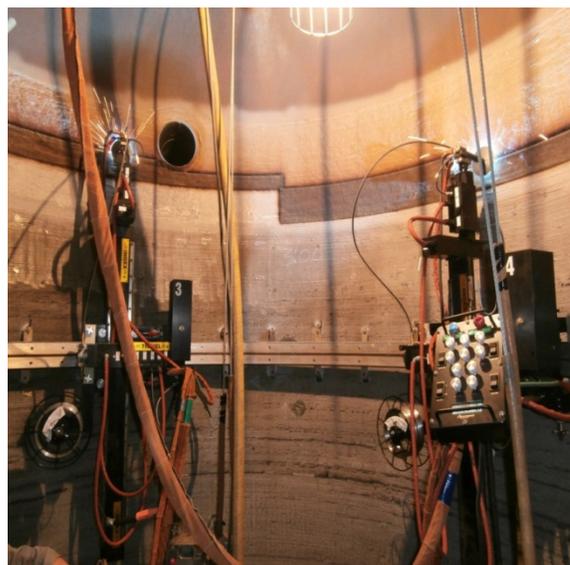


Figure 7: Automated weld overlay in progress

FATIGUE TESTING

In 2008, parallel to the first weld overlay repair, a fatigue test program was launched in two phases. The objective of the program was to assess and optimize the performance of engineered weld overlays for long-term repairs of coke drums. The motivation was that, if repairs can reliably postpone replacement for a significant period of time, the potential savings in cost and disruptions to operations would be substantial.

Phase 1 was a feasibility study that utilized a C-½Mo plate that was recovered from a retired drum that was in operation for 20 years. Test coupons were weld overlaid using Inconel 625. Ambient temperature load-controlled fatigue tests were conducted on three configurations: (1) base material + clad (unrepaired condition), (2) base material + weld overlay (repaired condition), and (3) as-welded overlay.

Phase 2 was a more comprehensive examination using the same retired plate and weld overlay material. Ambient as well as high-temperature testing (925°F) were performed using load-controlled as well as standard fully reversed strain-controlled fatigue tests. Test coupons were obtained for two additional configurations: (1) base material + clad + weld overlay (proposed unconventional approach of applying weld overlay onto clad), and (2) retired base metal.

In both phases, mechanical testing, metallurgical examinations, and nondestructive evaluations were performed. All fatigue tests were isothermal. After this program was initiated, several other operating companies and one welding contractor have performed similar test programs results from only one of which have been published [8].

The following is a summary of some key findings:

- Valuable unpublished properties were obtained for in-service base metal and as-welded Inconel 625 overlay that can be used for performing realistic fitness-for-service assessments of repaired drums.
- At constant temperature, the standard weld overlay process (overlay on base metal) significantly improved the fatigue life of test coupons both in ambient and high-temperature tests.
- The proposed unconventional weld overlay on clad improved fatigue performance even more. However, since tests are isothermal, the effect of thermal cycling on the three-layered coupons was not reflected in results. No separation between the clad and base was found due to weld overlay on clad.
- The base metal has not hardened substantially over its service life and has maintained its strength.
- When overlay was applied on clad, the base metal at the clad interface did not harden during the weld overlay process. The clad layer is hardened at the weld overlay interface, but this effect was limited in depth. The maximum hardness observed is near the upper limit that can be obtained with such alloys.
- Measured fracture toughness of the retired coke drum base metal was better (higher) than the published minimum values used in fitness-for-service assessments.
- Surface cracks present in both the base metal and clad surfaces due to coker service did not appear to propagate during fatigue testing.
- Most of the failure origins in the unrepaired specimens were located at the clad layer. Most

failure origins in the weld overlay specimens are at the as-welded surface.

- Residual stresses at the surface of the weld overlay and the free surface of the base metal correlated well with a detailed finite-element simulation of the weld overlay process.
- Surface notches on the weld overlay surface that contain slag from the welding operation did not appear to initiate fatigue cracks.
- A commercially available device for measuring surface roughness was identified for reliably measuring roughness against overlay weld passes and replicas.

RESULTS

Since implementing the new integrity management system, fundamental changes to unit behavior were observed, as described below.

First, bulging severity did not only stabilize but also decreased. This means the bulges have actually straightened up and became less severe. So, while the initial purpose of weld overlay repairs was to stop bulging deterioration and extend fatigue life, reductions in bulging severity has come about as a side effect of residual stresses that were created by the welding process. Figure 8 shows the collective bulging severity trend of all the U1 drums together. It shows a downward trend indicating that drums bulging have collectively improved. This improvement is dramatic and unique in the coker industry. The consequence of the improvement is a longer predicted economic life of the drums and a reduced need for inspections.

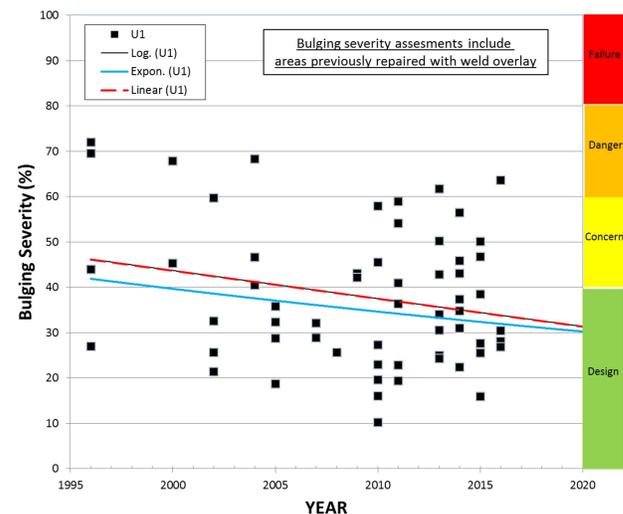


Figure 8: Bulging severity trend of U1 drums

In addition to the decrease in bulging severity in U1, drum cracks have stopped after the above program was implemented. Since 1986 when the first cracks were discovered at one bulge in one drum, the number of cracks significantly increased over time until the new integrity strategy was implemented. Since then, cracks

were mostly found at circumferential seam welds, as required by the inspection routine, or at bulge areas that were predicted by the assessment methodology.

Two implementation-related issues have been reported:

1. Some cracks were observed at the toe of perimeter weld where the weld overlay joins the clad. These cracks, which are usually found in the clad, sometimes progress into the base metal and cause corrosion damage. Improved techniques to better transition between the weld overlay and cladding are being developed and implemented.
2. A couple of cracks in as-welded overlays have been reported. Failure examinations suggested that large stress risers from poor weld surface finish are likely responsible for this rare type of failure. Efforts to develop guidelines to improve weld surface finish are underway.

Since 2009, U1 drums had a successful run. Operating experience and every inspection to date have shown the program to be successful in extending the life of the drums and preventing through wall leaks. The overall condition of these drums has improved substantially.

Obviously, through-wall leaks are of concern to Plant personnel as well as to Alberta's delegated regulatory authority - ABSA. The new mechanical integrity program has mostly eliminated that risk. To ensure that past success is maintained, the program is planned to be continued.

Based on a thorough review of drums performance, the extension of inspection intervals of U1 drums from three to four years is being considered. This extension would save maintenance cost and provide additional production that would otherwise be lost due to turnarounds. The combined savings would be spread out over the four year cycle and represent around \$30 million per year for the four sets of drums collectively.

As a result of the fatigue studies that showed that the weld overlay could significantly extend the life of drums and the inspection in 2010 that showed no defects in the 2008 repairs of 5C-6, the project to replace U1 coke drums was cancelled in 2011.

Bulging severity trend of U2 drums is shown in Figure 9. These drums, which did not use the same mechanical integrity strategy, show a significant increase in the severity of bulging damage over time.

A comparison with the U1 chart of Figure 8 indicates that the new integrity management process has resulted in a drastically different performance that will likely lead to longer economic life and a reduced inspection effort for the drums.

In examining and comparing the charts of Figure 8 and 9, it is important to note the influence of the following factors on scatter and trends:

- a) The age of drums significantly varied within each set. As explained above, U1 comprised six drums commissioned in 1967 and two in 1981. U2 comprised four drums commissioned in 2001 and two in 2008.
- b) U2 drums have dual side inlets and are made of 1 Cr whereas U1 drums have bottom inlets and have a mixture of C 1/2 Mo and 1 Cr drums.
- c) Not all drums in each set were laser-scanned every time,
- d) Not all bulges in all drums were repaired using weld overlay at the same time,
- e) The condition of drums significantly varied. While some drums experienced repeated bulging-induced through-wall cracks, others had none, and
- f) The amount of noise in laser data is dependent on the technology and the condition of inspected drum.

Because of the above, data in the charts have a significant scatter and can only be used in a directional manner.

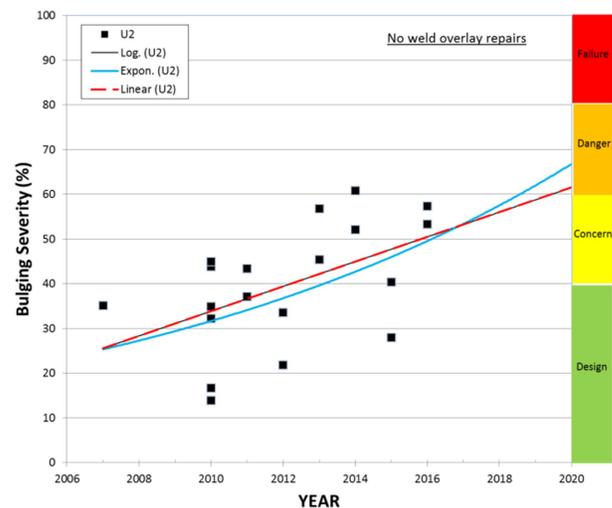


Figure 9: Bulging severity trend of U2 drums

FUTURE WORK

To improve and fine tune the above integrity management strategy, several improvements are needed and are being examined the most important of which is the development of surface finish guidelines and inspection methods for weld overlays. Such development is necessary because of the following:

- The inability of inspectors to determine the acceptability of weld overlays without a clear standard,
- The inconsistent quality of automated weld overlays among service providers and even within the same

company. An example of a poor surface finish is shown in Figure 10.

- The conclusion that shop-made test specimens are not a feasible guide for field work.

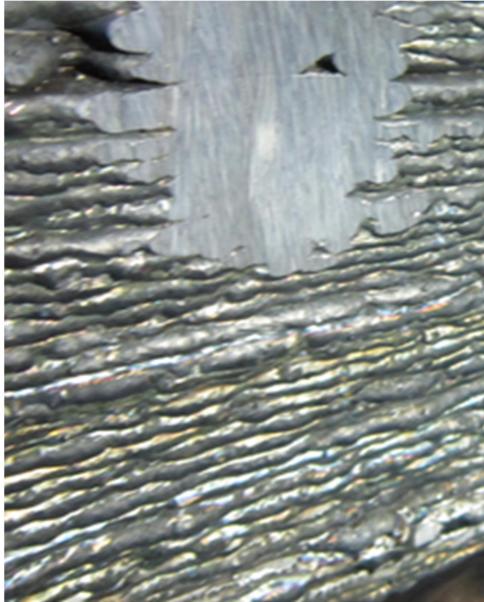


Figure 10: An example of a poor field weld surface with sharp grooves

One possible way to address this concern is to require grinding weld overlays smooth, but this can be very costly and time consuming especially for large-scale repairs. Therefore, in order for these repairs to realize their full potential, operating companies must have the ability to ensure a minimum level of quality for weld overlay surfaces in a field work environment which can only be accomplished by the ability to: (a) measure field surface roughness in a practical and timely manner, (b) determine the acceptability of a measured roughness using a performance-based criterion, and (c) repair areas that fail the criterion before the repair job is complete. Effort is underway to develop the tools needed to accomplish this goal.

CONCLUSIONS

A new mechanical integrity strategy was implemented on a set of eight coke drums in Canada. The core of the strategy is the use of internal laser scanning, strain-based bulging assessment, and weld overlay repairs to preempt crack development. As a result, bulging deterioration rate and crack development in this set of drums have not only slowed but reversed. Despite the fact that they are among the oldest and thinnest drums in operation in the world, these drums have become very reliable. Unpredicted cracking and through wall cracks have been eliminated.

The project to replace these coke drums was cancelled and the extension of inspection intervals from three to four years is being considered. The projected combined savings from inspection interval extension alone is approximately \$30 million per year. This improvement is dramatic and unique in industry.

In contrast, a second set of drums at the same plant that was not included in the same management strategy has deteriorated at an increasing rate despite their much younger age and thicker walls.

The success of this new mechanical integrity strategy promises to change the long-term economics of coke drum operations.

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