# FUNDAMENTAL UNDERSTANDING OF CRACKING AND BULGING IN COKE DRUMS

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## ABSTRACT

Cracking and bulging in welded and internally lined pressure vessels that work in themal-mechanical cycling service have been well known problems in the petrochemical, power and nuclear industries. However, published literature and industry surveys show that similar problems have been occurring during the last 50 years. A better understanding of the causes of cracking and bulging causes is needed to improve the reliability of these pressure vessels. This study attempts to add information required for increasing the knowledge and fundamental understanding required.

Typical examples of this problem are the coke drums in the delayed coking units refinery process. This case was selected for experimental work, field study and results comparison. Delayed coking units are among the refinery units that have higher economical yields. To shut down these units represents a high negative economical impact in refinery operations. Also, the maintenance costs associated with repairs are commonly very high. Cracking and bulging occurrences in the coke drums, most often at the weld areas, characterize the history of the operation of delayed coking units. To design and operate more robust coke drums with fewer problems, an improved metallurgical understanding of the cracking and bulging mechanisms is required.

A methodology that is based field experience revision and metallurgical analyses for the screening of the most important variables, and subsequent finite element analyses to verify hypotheses and to rank the variables according to their impact on the coke drum lives has been developed. This indicated approach provides useful information for increasing coke drum reliability.

The results of this work not only order the most important variables according to their impact in the life of the vessels, but also permit estimation of the life spans of coke drums.

In conclusion, the current work shows that coke drums may fail as a combination of thermal fatigue and other degradation mechanisms such as: corrosion at high and low temperatures, detrimental metallurgical transformations and plastic deformation. It was also found that FEA is a very valuable tool for understanding cracking and bulging mechanisms in these services and for ranking the design, fabrication, operation and maintenance variables that affect coke drum reliability.

**KEYWORDS:** Pressure Vessels, Coke Drums, Fatigue, Bulging, Cracking

## BACKGROUND

Delayed coking is a thermal cracking oil refinery process that converts heavy hydrocarbon (bottoms from atmospheric and vacuum distillation unit of crude oil) into lighter more valuable products and coke. The unit is normally divided in coking, fractionation and gas concentration sections. Figure 1 shows a typical simplified flow diagram of the coking section where the coke drums are located. The feed to the delay coker unit is preheated in a furnace from room temperature up to 920-950°F. With short residence time in the furnace tubes, coking of the feed material is thereby delayed until it reaches the coke drums. In the coke drums, separation between lighter hydrocarbons (liquid and gas streams) and coke is produced due to thermal cracking of the hydrocarbon molecules. The lighter products exit from the top of the drum and flow to a fractionator, whereas the coke is adhered to the vessel wall and will be mechanically removed at the end of the coking cycle.

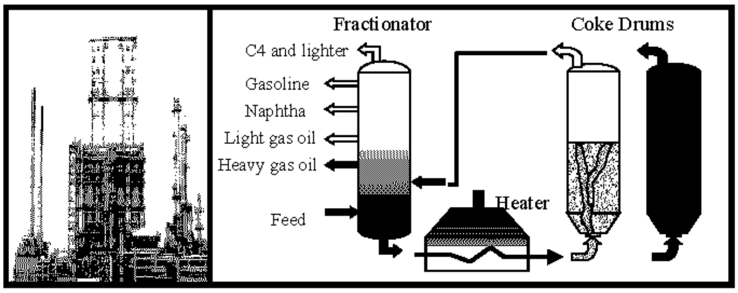

Figure 1 - Flow diagram

A typical thermal cycle used in the operation of the drum is shown in Figure.2. The cycle involves steam and vapor preheat, fill, steam and water quench and cleaning. Feed temperature to a coke drum, as mentioned before, is 920 to 950 °F; outlet temperatures are 800 to 820 °F. The operating pressure ranges from atmospheric to 75 psi. The entire cycle lasts between 24-48 hours. They operate mostly in pairs to permit the continuous operation of the unit. Only the coke drum section operates in batch mode.

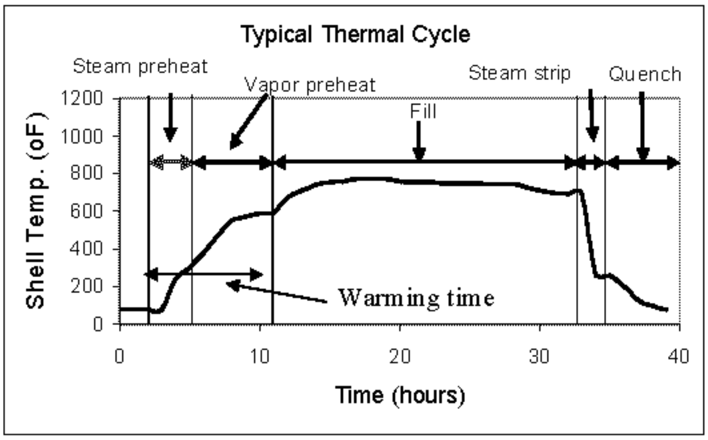

Figure 2- Thermal Cycle

These pressure vessels are 13-30 feet in diameter and 80-100 feet in height. Since the common feedstock for these drums includes hydrocarbon with relatively high sulfur content and the operating temperature are as high as to 950°F, the coke drums need internal protection against sulfidation and carburization. Plain carbon steels and low alloy steels have been standard materials for these applications. However, to protect these materials from sulfidation, a common approach has been to include a martensitic (410S) or ferritic (405) stainless steel clad plate. These materials contain 11.5-14.5% Cr that reacts with sulfur to form chromium sulfide in sulfidizing environment. Chromium sulfide acts as a protective barrier from the environment, thereby decreasing the corrosion rate. It is believed that the coke layer formed on the drum internal surface will protect the wall from sulfidation. The coke protective effect may explain the fact that high Ni alloy weld repairs have been successfully used for clad repair in this service, while in other sulfidizing refinery environments they will corrode at higher rates. Alloys containing higher Ni contents have also been shown to be more resistant to carburization than alloys with lower Ni content [1]

Welds play an important role in the life of these vessels [2], and it is very common to find cracks in the weld areas. Standard welding procedures will use single or multiple combinations of shielded metal arc welding (SMAW), submerged arc welding (SAW), gas metal arc welding (GMAW), and gas tungsten arc welding (GTAW) processes. When clad plates are welded, different filler alloys may be used to complete the weld. The carbon steel or low alloy steel is welded using matching filler metals. The stainless steel clad is welded with austenitic stainless steels i.e. AWS A5.9 E309 or with high Ni alloy fillers such as AWS 5.11 E-NiCrFe3 or ERNiCrFe2 or AWS 5.14 ER-NiCr-3. A typical weld is shown in Figure 3.

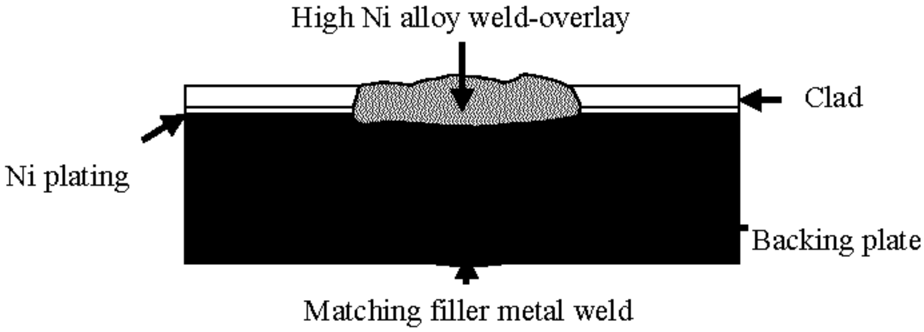

Figure 3- Weld detail

## FAILURE DRIVING FORCES

Coke drums fail at different operation lives. However, the failure frequency increases with increasing age. Typical time spans required for through wall cracking occurring range from 3000 to 5000 cycles. However, some refineries have reported through wall cracking after shorter time periods. In fact, it is not uncommon to experience cracking and bulging within the first 5 years of service. The thermal stresses in the vessel have been measured and found to be above yield. Axial and hoop stresses in a coke drum can peak as high as 120,000 and 115,000 psi respectively, with average axial and hoop stresses being around 48,000 and 40,000 psi respectively. Axial peak stresses appeared to exceed 80,000 psi for less than 10% of the cycles investigated, and 5% for the hoop stress [3]. These cycles produce very large stresses that should play very important roles in defining the drum lives.

The combination of high temperature and high sulfur content in the hydrocarbon stream create an environment that enhances the rate of sulfidation. Sulfur reacts with iron, chromium, and nickel. Chromium sulfide and oxides provides better corrosion protection when compared to iron or nickel sulfide and oxides. The combination of fatigue and corrosion can interact synergistically. The relatively high process temperature, consequently high wall temperature in the drums is above the brittle-to-ductile-temperature transition, which may lead to a leak-before-failure mode. Catastrophic failures are not typical in this service. However, to correct the leak requires shutting down the unit, which may result in undesirable operational losses to a refinery [4].

## HYPOTHESES

The potential causes for cracking were related to low cycle thermal fatigue, corrosion, and metallurgical degradation. Potential causes of bulging are fabrication misalignment, plastic deformation, creep, residual stresses, strain ratcheting, and cold/hot spots. The fatigue problem may be associated with thermo-mechanical fatigue, fatigue-corrosion, and fatigue-creep. The corrosion mechanisms were divided as low temperature corrosion including pitting, galvanic and intergranular corrosion, and high temperature corrosion such as sulfidation and carburization. Among the metallurgical degradation mechanisms are temper embrittlement, reheat cracking, carbon and element inter-diffusion and quench cracking.

## METALLURGICAL ANALYSES

Optical and Electron Scanning Microscopy. Several field samples from different refineries have been analyzed in the Welding Engineering laboratories and the Materials Science Engineering laboratories at the Ohio State University. These samples were obtained from different backing, clad and filler weld materials. The samples analyzed had been in service for 14-30 years. Two samples were extracted from clad plates, and analyzed for comparison before placing them in service. The following paragraphs summarize the significant findings from these analyses.

Figure 4 shows striations and parabolic shear dimple holes, which are typical fatigue marks. These striations were found in a repair-welded with high Ni alloy filler. Surface cracks were developed and the faces of the crack were opened for evaluation. These striations in coke drums are normally destroyed due to corrosion and fretting. However, the striations in the figure were observed at a location very close to the crack tip where the fretting and corrosive effects were not sufficient to eliminate the fractographic evidence of fatigue It is important to note here that sample had been in service for 28 years when the sample was removed. The distance between striations is approx. 1 μm. This distance can be associated to the distance that the crack advances each cycle. Extrapolating this crack growth rate, and assuming it is constant, cracks will growth 125 mils every 3000 cycles. This represents more than 12 years of growth (36 hours/cycle). Crack growth rate may also change depending on: (i) the material in which the crack tip is located, and (ii) the stresses generated by the operational conditions.

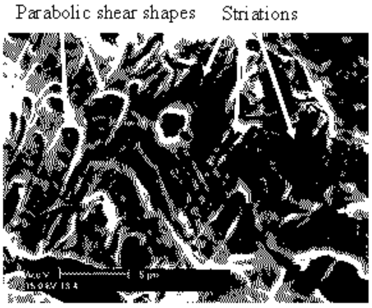

Figure 4- Striations

Figure 5 shows typical shallow cracks found in the clad surface. This sample was taken from the same drum where striations were found. The backing material in this sample is 1Cr ½ Mo with 410S clad. Similar cracks were found in all in-service samples regardless of material type.

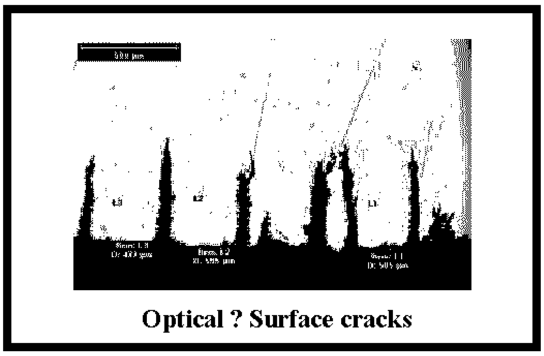

Figure 5- Shallow cracks

Carburization and sulfidation were observed in the clad, high Ni alloy weld deposit and base metal. In all these cases different layers of corrosion products were observed on the plate and crack surfaces. The concentrations of C and S are high in the surface as expected. In the case of the clad the surface layer has a C and S content of 51 and 17% (wt.%) respectively. The microhardness of the surface layer is 160 Vickers. The sub-surface layer has 14 and 2 (wt.%) C and S concentration. The microhardness in this subsurface layer is higher than 400 Vickers. The Cr content of the surface layer was approx. 1% while the Cr content in the subsurface layer is 47%. This means that the sub-surface layer is enriched in Cr. The Cr is likely to react with C and S, resulting in the formation of chromium sulfides and chromium carbides, respectively. As discussed earlier, the chromium sulfide provides corrosion resistance to the clad. The outer layer is composed from iron sulfide with is less corrosion resistant at high temperatures.

Intergranular cracking is observed on the surface of the clad. Intergranular cracking is believed to occur due to chromium carbide precipitation, which increases the rate of the intergranular sulfidation process. For chromium sulfide formation, Cr needs to be free and not be attached to C in carbides.

In the case of the high Ni alloy weld deposit the surface layer contents 44%C, 15%S, 5%Fe, <1%Cr and 25%Ni, whereas, the subsurface layer has a composition of 6%C, 9%S, 28%Cr and 8%Ni. We can infer that Ni sulfide and Cr sulfides are primary formed at the surface and subsurface layers respectively. Ni sulfide does not provide as good barrier to corrosion resistance as Cr sulfide does. In the high Ni alloy weld, crack growth occurs preferentially along the interbead regions, and also along the grain and sub-grain solidification boundaries.

In the case of the base metal, Cr is not available for the formation of chromium sulfide. Corrosion rates are, therefore, faster. Also, fatigue crack propagation is faster in ferritic steels when compared to austenitic stainless steels and high Ni [5]. Figure 6 shows crack propagation into the base metal.

In all the cases it was observed that cracks are present in the corrosion products layers that help to transport C and S to the crack tip. This supports the hypothesis that a fatigue-corrosion mechanism is the driving for crack propagation.

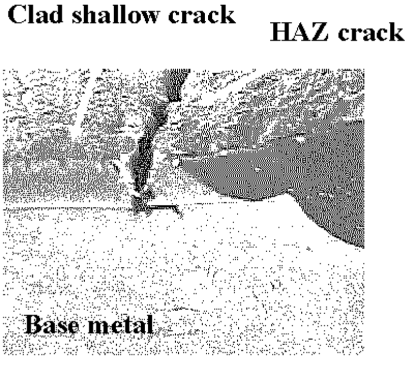

Figure 6- Heat affected zone crack

The differences between the thermo-mechanical properties of the materials that are joined at the interfaces, and the additional degradation mechanisms that are induced at the joints, can lead to the development of a strength mismatch. The mechanical strength mismatch can lead to strain ratcheting. The interfaces that can be produced include: base metal (backing) / weld metal (matching), base metal (backing) or weld metal (matching)/high Ni alloy weld, clad/high Ni alloy weld, and base metal (backing) and weld metal (matching)/clad. These interfaces include heat-affected zones where carbide precipitation, recrystallization and grain growth occurred. Again, as mentioned earlier in this paper, large concentration profiles in fusion boundaries can introduce regions of brittle martensite, unmixed zones and grain boundaries parallel to the fusion boundary between martensite and austenite, that are susceptible to cracking. The samples where these microhardness profiles were taken were fabricated from carbon ½ Mo plate with 405 SS clad and 1Cr 1/2Mo plate with 410S SS clad. Matching chemical composition weld metal and high Ni alloy filler were used for base metal and clad welding respectively. The samples were removed after 28 and 30 years in service.

## FINITE ELEMENT ANALYSES

The first part of the FEA was accomplished to review some of the hypotheses. Field skin thermocouples and strain gages in the shell and skirt were used to calibrate the models. After calibration was accomplished the internal heat convection coefficients, sink temperatures and pressure were tied and only other process and design variables were change. All FEA subroutines were elaborated to simulate the coking cycle. The subroutines calculate the heat convection coefficient, sink temperature, and pressure inside the vessel in function of height and time (see figure 7). FEA results show how plastic strains can be accumulated during the heating and cooling part of the cycle. Axial and radial temperature gradients are high enough to generate thermal stresses above the yield stress of the material. The accumulation of plastic strain (strain ratcheting) produces bulging. Reverse bending that occurs in the skirt-shell joint causes fatigue. Joint geometry and insulation design affects greatly the distribution of stresses. Another important results is the description of how the physical, thermal and mechanical property mismatch between the backing and lining plate of the clad can produce plastic strain in the lining plate of the clad. This accumulation of plastic strain in the lining plate can explain the formation of shallow cracks in the lining. The effect of the mismatch in the shell dissimilar welds is shown in Figure 8. Plastic strain accumulation occurs in the clad heat affected zone and others metallurgical interfaces.

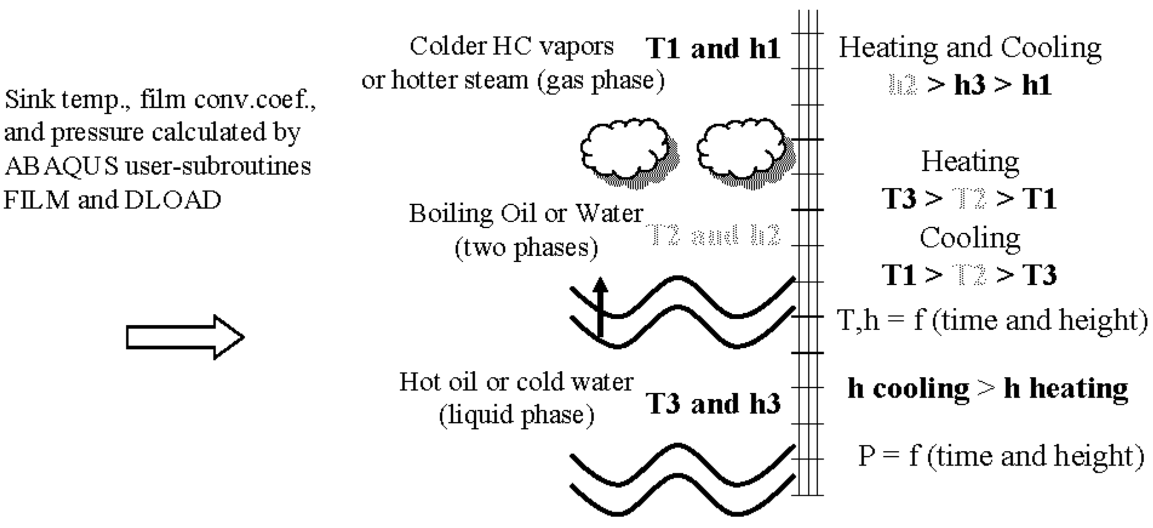

Figure 7- FEA sub-routine

Once the subroutine and model were calibrated some of the most important variables were selected for a parametric study. These variables were heating and cooling rates and warming time (process variables) and material property mismatch, shell and skirt plate and insulation geometry (thickness, length, diameter, curvature radii), keyholes geometry.

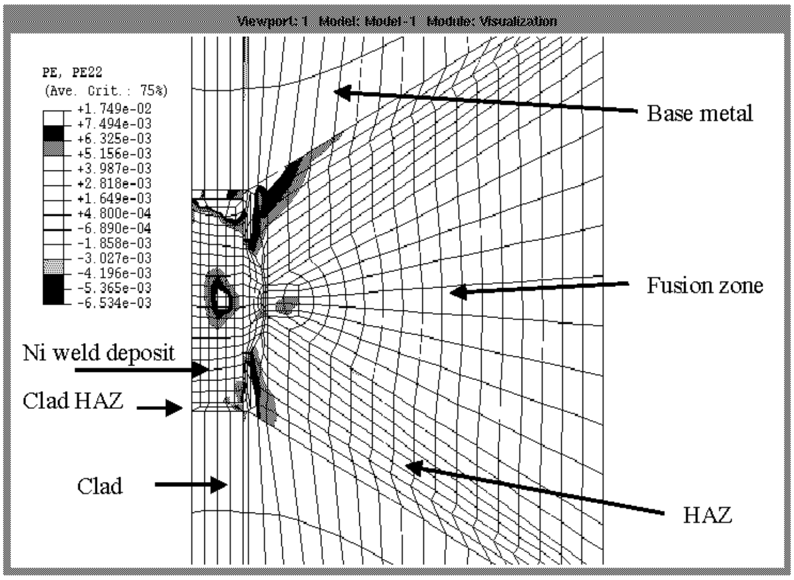

Figure 8- FEA weld strength mismatch

## 4- CONCLUSIONS

A fundamental explanation of the occurrence of bulging and cracking in pressure vessels in multiphase environments has been developed. Several important factors have been identified including the high convection coefficient of the boiling layer during filling and quenching, the mismatch in physical, thermal and mechanical properties in the dissimilar weld of the clad plates, process conditions such heating and quenching rate and warming time, and the geometry of the weldments. The combination of the high convection film coefficient at the boiling layer and operating conditions lead to thermal stress gradients high enough to explain the bulging formation of the shell plates. Operating conditions such as heating and cooling rates and warming time have been shown to have important roles in the level of temperature and thermal stress gradients.

Coke drums work under a combination of thermal-mechanical low cycle fatigue and other degradation mechanisms such as corrosion at high and low temperature, detrimental metallurgical transformations and plastic deformation. Metallurgical evidence of the degradation mechanisms concurrence has been found. Even though the variables mentioned before are very important factors in crack initiation and propagation, the fact that corrosion interaction with the process of crack initiation and propagation has been identified in the metallurgical analysis should not be underemphasized. However, the relative affect of the corrosion aspect when compared to the other variables has not been precisely defined. The impact of corrosion on crack initiation and propagation can vary from case to case because the amount of contaminants such as S and its different compounds in the feed varies as well. Corrosion at low temperature depends on the amount of contaminants in the quenching water, which includes sulfides, ammonium and chlorides. The amount of these contaminants varies among refineries.

## ACKNOWLEDGEMENTS

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