BAHX Fatigue - Smart Layer® Indications versus Simulation Estimations

Detection vs Prediction

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ABSTRACT

The ability to predict and detect fatigue damage in brazed aluminum heat exchangers (BAHX) is a topic of interest for many. Predicting damage relies on computer models that simulate the response of BAHX as they react to changing operating conditions. Until recently, detecting fatigue damage in BAHX relied on waiting until a process leak occurred. However, with the introduction of Smart Layer, actual fatigue damage can be detected in the field prior to process leaks occurring. There are advantages and difficulties with current fatigue prediction methods and fatigue detection methods, but both play a role in ensuring safe and profitable use of BAHX.

Introduction

The ability to predict and detect fatigue damage in brazed aluminum heat exchangers (BAHX) is a topic of interest for many. Predicting damage relies on computer models that simulate the response of BAHX as they react to changing operating conditions. Detecting fatigue damage in BAHX has traditionally relied on waiting until a process leak occurred. However, with the introduction of Smart Layer, actual fatigue damage can be detected in the field prior to process leaks occurring. There are advantages and difficulties with current fatigue prediction methods and fatigue detection methods, but both play a role in ensuring safe and profitable use of BAHX.

Background

Brazed aluminum heat exchangers serve critical roles in various industrial processes, including low-temperature natural gas, air separation, and petrochemical processes around the world. These are compact and versatile devices that are adaptable to many different processes, but they excel at managing multi-stream cryogenic processes where close temperature approaches are desired.

The compact construction and high heat transfer efficiency of BAHX also means that large temperature differences and large temperature rates of change can induce thermal strain in the exchanger and lead to thermal fatigue. Operating guidelines concerning suggested maximum allowable temperature differences and temperature rates of change are covered in the ALPEMA® standard and in the Chart® Installation, Operation, and Maintenance manual. These guidelines aim to mitigate thermal gradients and minimize thermal fatigue damage. They are deliberately designed to be conservative to account for all the variations in design and circumstances that can arise.

For many situations, exceeding the guidelines will not result in appreciable fatigue damage to the heat exchanger. In rare instances where fatigue damage does occur in a BAHX, the most common symptom is cracked sheets resulting in minor leaks. Since leaks can result in costly unplanned plant shutdowns, owners and operators are interested in predicting and detecting thermal fatigue before it becomes an issue.

Fatigue Basics

Stress, strain, and fatigue can be induced mechanically or thermally. Repeated bending of a paper clip is a classic example of mechanical fatigue. Thermal fatigue, in contrast, is caused by constrained thermal expansion or contraction. An example of this is a bar that is repeatedly heated and cooled with the ends locked in position.

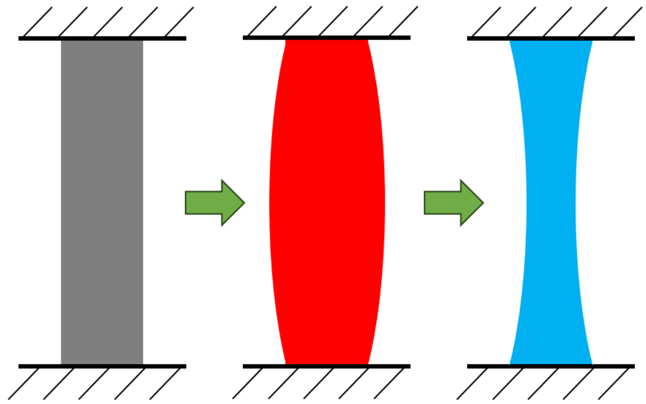

Figure 1: Constrained bar thermal strain example

Fatigue is caused by changing stress or strain states over time, referred to as cycling. The number of cycles at a given stress/strain amplitude before a macroscopic crack is formed is the fatigue life. Fatigue life is typically a high-cycle phenomenon, with fatigue lives measured in the tens of thousands to millions of cycles. However, low-cycle fatigue also exists, with fatigue lives measured in the hundreds of cycles.

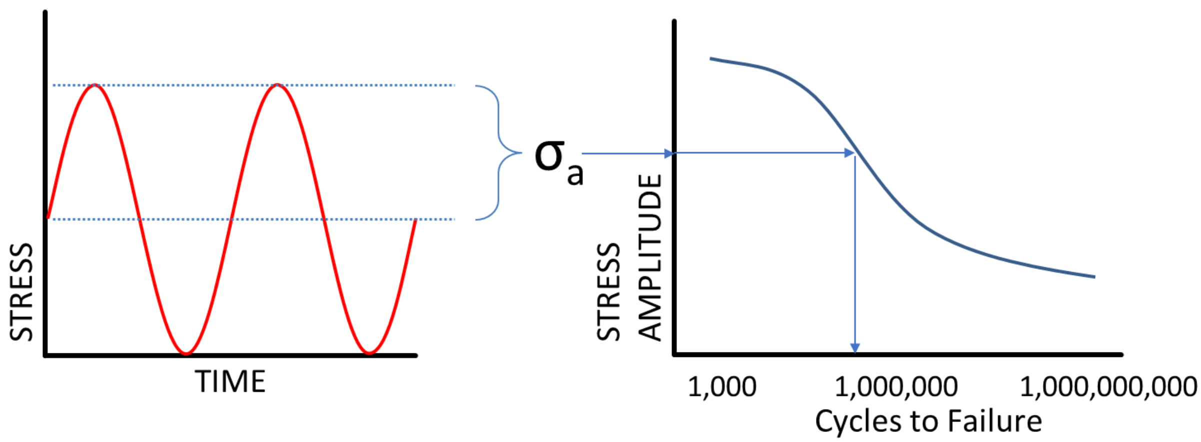

Figure 2: Alternating stress conversion to fatigue life

Fatigue life as a function of stress or strain amplitude is called the fatigue curve. These curves are unique for different metals, treatments, and loading scenarios. They are developed by constructing identical samples and applying carefully controlled cyclic loading until each specimen breaks. Even laboratory fatigue data taken under ideal scenarios is notorious for the scatter it contains. For example, given two identical test pieces subjected to the same test regime, it is not unusual that one might experience fatigue failure after 300,000 cycles while the other might not experience failure until 6,000,000 cycles.

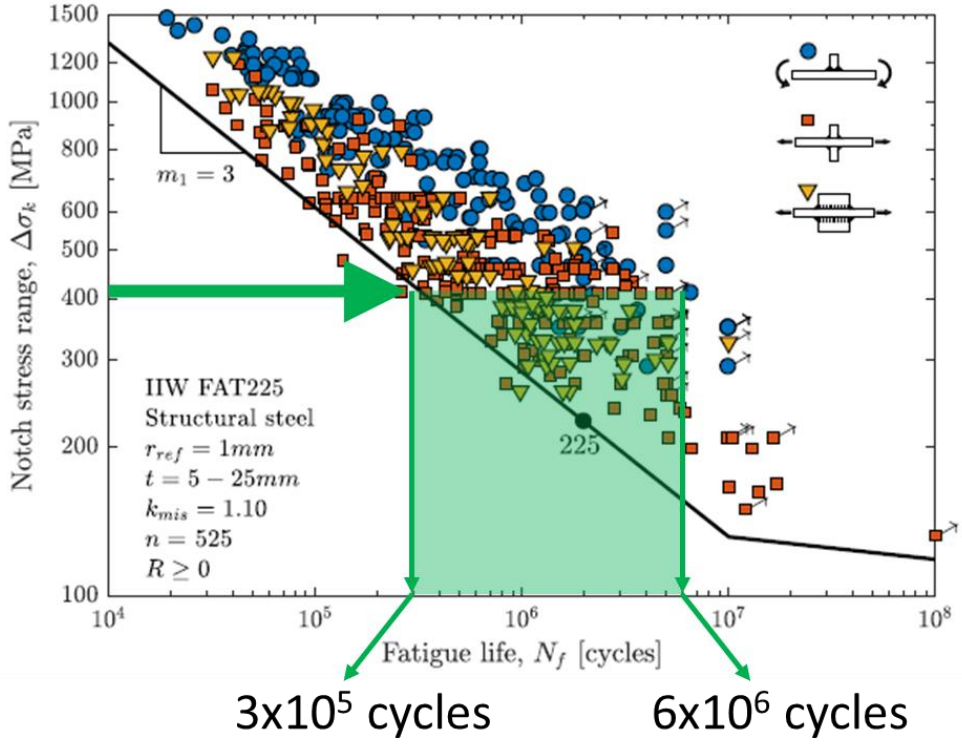

Figure 3: Example fatigue data courtesy of FatigueToolbox.org

Fatigue in BAHX

Thermal fatigue is a major factor in determining the operational life of a BAHX. Transient operating conditions, or even fluctuations in steady state process conditions such as with unstable boiling, will create changing thermal gradients. These cause fluctuating stress states in the BAHX, which drive fatigue crack formation. A BAHX that is operated continuously at steady state will theoretically have an indefinite life, but practically speaking all equipment will experience some fatigue, even if it is negligible.

Fatigue in BAHX primarily manifests as small cracks in the sheets near the outside of the stack. These cracks are typically located on the inside perimeter of the bars, often around header attachment points. Cap sheet cracks will cause process fluids to leak externally to the BAHX, while parting sheet cracks will cause high-pressure streams to leak into adjacent low-pressure streams. Parting sheet cracks are typically more difficult to detect and locate.

BAHX Fatigue Simulation

Simulation Basics

Predicting fatigue in a BAHX is based on using computer models to simulate the response to changing operating conditions. First, the computer model is built using the construction details of the heat exchanger, including layer types, stacking pattern, fin types, and fluid compositions. Next, dynamic process conditions are input into the model. These can be actual measurements taken from field data, or output from dynamic process or plant simulations. This must include inlet flow rates, temperatures, and pressures for each stream, typically provided at 1-minute intervals for the entire duration of the simulated event.

The computer simulation occurs over three stages. In the first stage, the thermal and hydraulic response of the BAHX is simulated. This is where the pressure loss and flow profiles along the width and stack height are calculated, and the heat transfer between streams and the different metal components are simulated. The output of this is a 3D flow, temperature, and pressure history of the fluid inside the exchanger and a 3D temperature history of the exchanger metal.

In the second stage, the fluid pressure history and exchanger metal temperature history are used to calculate the internal stresses in the BAHX at different time steps during the event. The output of this is a 3D stress history for all points inside the heat exchanger structural components.

In the third stage, the stress history is fed into a fatigue simulation. This is where the stress tensor history at each point is analyzed, and the fatigue damage is calculated. The output is a predicted fatigue life for each point in the heat exchanger structure. The point with the lowest predicted fatigue life is the location where the first crack should appear, and the fatigue life of this point is the fatigue life of the BAHX for the simulated event.

Simulation Difficulties

There are difficulties with using simulations to predict real world BAHX fatigue, most of which are related to the assumptions that must be made and how they compound on each other.

The first difficulty is the assumption that the dynamic event details are known. When field data is used as the simulation input event data, often this data is incomplete. It is typical that not all the instrumentation to fully define the flow, pressure, temperature, and composition of each stream during the event is present. The missing data can be reconstructed, but this process is based on making more assumptions. Additionally, there is uncertainty in the instrumentation itself, for example where the instrument is reading 12 but the actual local value is 11. There is also a response lag, where the process value is moving and the inertia of the instrument means that it is slow to react, and different instruments typically have different response times. Lastly, instrument location can mean the BAHX is experiencing inlet conditions that are different than what an instrument located 200 ft upstream is reading.

The second difficulty is the assumption that BAHX will experience the same simulated event repeatedly. A BAHX operates as part of a large, complex system, and inlet conditions are affected by many different variables. These variables are constantly fluctuating; operators are constantly trying to correct small process deviations, and equipment, procedures, and feed gas compositions change over time.

The third difficulty is the assumption that the behavior of each computer model matches reality. All models must contain simplifying assumptions that approximate reality but never perfectly recreate it. Assumptions about both material properties and material behavior theory are among those that compromise this difficulty.

Material properties vary from batch to batch, and the properties of a specific BAHX will undoubtedly deviate slightly from the average. Additionally, obtaining high quality data on temperature dependent material properties, especially at cryogenic temperatures, can be challenging.

Material behavior can also be modeled according to different theories. Different finite element theories such as kinematic hardening models and small or large deflection models have different assumptions about how materials behave. Fatigue theories applicable to non-proportional variable amplitude loading and damage accumulation models also affect how the simulation predictions are made.

The last assumption worth mentioning is how the computer model matches the actual installation. Residual pipe loads, support structure and ship motion loads, insulation, and heat leak can also cause simulation predictions to deviate from reality.

These assumptions are layered on top of the inherent scatter of the underlying fatigue data. Fatigue life in real-world conditions will only increase the already significant variability in fatigue life measured under ideal laboratory conditions.

Simulation Use Cases

The above commentary is not to say that simulations are not useful, but that the absolute results they produce must be carefully considered. Simulations can be helpful in assessing the relative severity and impact of different events. One circumstance where this has been historically needed is when setting equipment safety integrity levels (SIL) as a part of Hazard and Operability Study (HAZOP). In this case, multiple potential failure cases are analyzed, and the relative predicted fatigue damage to the BAHX was used to set SIL. Another circumstance where simulation predictions have been useful is in developing control strategies and response procedures for different upset conditions. Different manual and automatic responses can be simulated and the ones with the lowest predicted damage put into production.

One area that simulations have not proven extremely useful is in designing individual BAHX to better withstand specific transient events. Although it could theoretically be used in this manner, experience has shown that this is rarely practical. The first reason is that the design principles that minimize thermal stress are already known and incorporated into the standard design process. The second is that the amount of time required to complete a simulation from start to finish, iterate on the BAHX design, and repeat would greatly delay the delivery time of a new exchanger.

Another area that simulations have not proven useful is in predicting the remaining life of already installed units. Quantifying the accumulated fatigue damage in an existing BAHX would require simulating the entire operating history. Attempts have been made to distill the operating history of a unit down to a few key transient events that are assumed to be most damaging to a heat exchanger, but this is very subjective, and the cost and effort required is approximately the same as buying a replacement unit. Furthermore, past events are often not very consistent with each other, and the probable deviation of future events from past events increases the uncertainty of the fatigue predictions even more.

Additionally, the scatter inherent in fatigue data would often lead to excessive uncertainty in predictions. Using the above example with laboratory data for fatigue life at a given stress amplitude spanning from 300,000 to 6,000,000 cycles, a cycle period of one minute would predict the fatigue life to be between 6 months and 11 years.

Simplified BAHX Fatigue Prediction

Attempts have been made in the past to use plant data to develop simple correlations to predict fatigue life. One such attempt was made by the GPA Midstream Association (GPA) circa 2019. The goal was to establish a database of BAHX operation and fatigue outcomes that members contribute to anonymously. The premise was that with enough data, machine learning 'big data' methods could be used to develop statistical correlations that would predict BAHX life without needing to rely on more sophisticated simulation methods. If done successfully, operators could apply the correlation to their operational data on a regular basis to predict the expected life of all their BAHX's at minimal cost and effort.

The distinction between a correlation and simulation is important here. Machine learning methods can develop complicated correlations given large sets of data, but the actual mechanics of failure are not considered. In contrast to this, simulation methods instead rely on the process of connecting changing metal temperatures to stress history, crack propagation, and fatigue theory to predict operational life. In other words, the machine learning method is more akin to a regression analysis relying only on operating data and ignores BAHX construction details that a simulation would consider.

The GPA contracted the University of Houston, known for their experience with aluminum fatigue, to perform a pilot study to explore the feasibility of the method. A small group of GPA members input their operating data and BAHX repair data into a shared database and machine learning models were used to attempt correlate operating data to heat exchanger life. The findings were presented in GPA publication RR-241 (Publications (midstreamassociation.org)) and concluded that no reliable correlation could be found between operating data and BAHX life. This does not mean that there is no connection between operation and BAHX life, but that it is dependent on BAHX construction details that must be accounted for using simulation models.

Concurrent with the above study, the Chemical Safety Board (CSB) was investigating the Enterprise Pascagoula Gas Plant Explosion and Fire. Prior to report RR-241 being published, the CSB recommended the GPA establish a database for collecting BAHX operational data and failure data to determine if any correlation between the two could be found (recommendation via csb.gov). Following publication of the GPA report, the CSB agreed that the 'big data' method was unsuitable for predicting fatigue life and rescinded their recommendation.

BAHX Fatigue Detection

Historically, there has not been any reliable way to detect fatigue damage in a BAHX prior to a crack appearing and process fluid leaking. With the introduction of Smart Layer® in 2018, units equipped with this technology can alert operators at the first sign of fatigue damage, allowing for defensive action to prevent a more serious loss of containment and emergency plant shutdown.

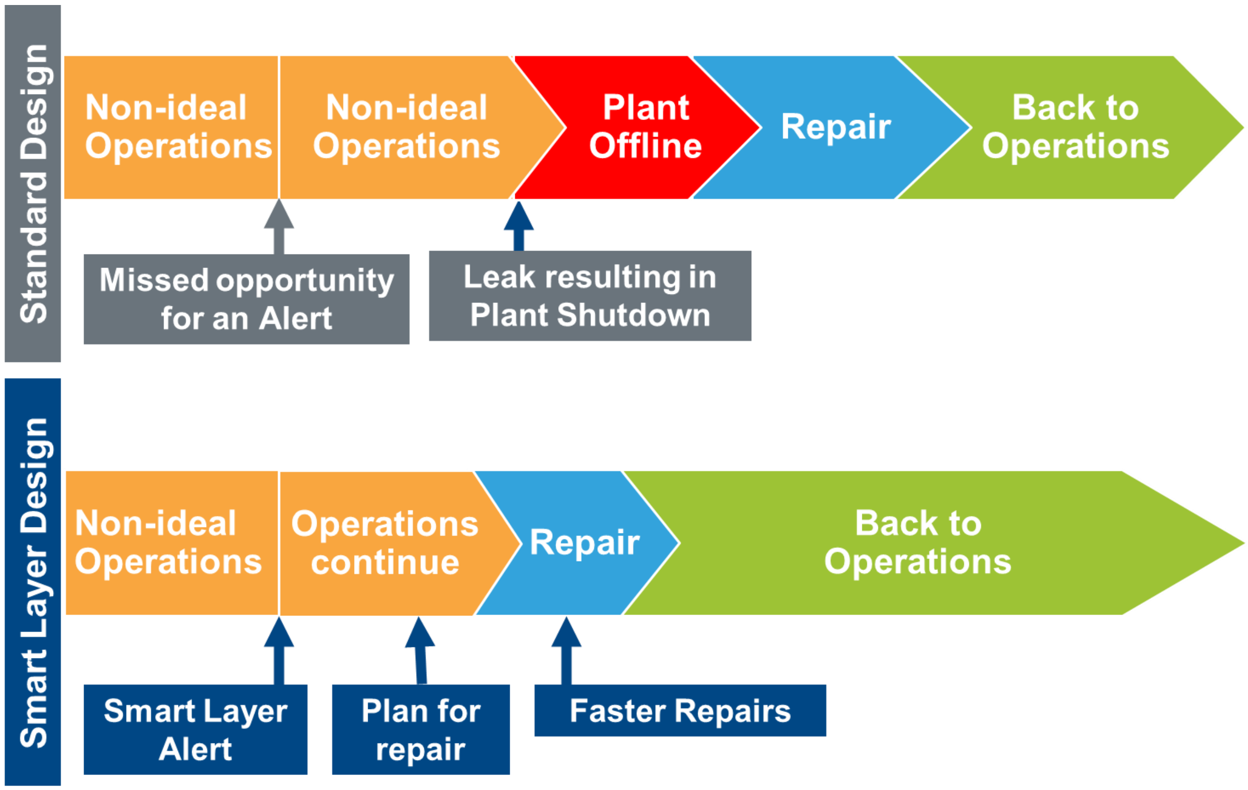

Figure 4: Smart Layer turns emergency repairs into planned repairs

Smart Layer operates on the premise that thermal fatigue typically accumulates fastest in the outside cap sheets and parting sheets. A fatigue crack through a parting sheet would result in cross stream contamination, while a fatigue crack through the cap sheet would result in a loss of containment. A loss of containment incident usually requires an immediate shutdown of the plant, leading to expensive expedited repairs and costing significantly more in lost productivity.

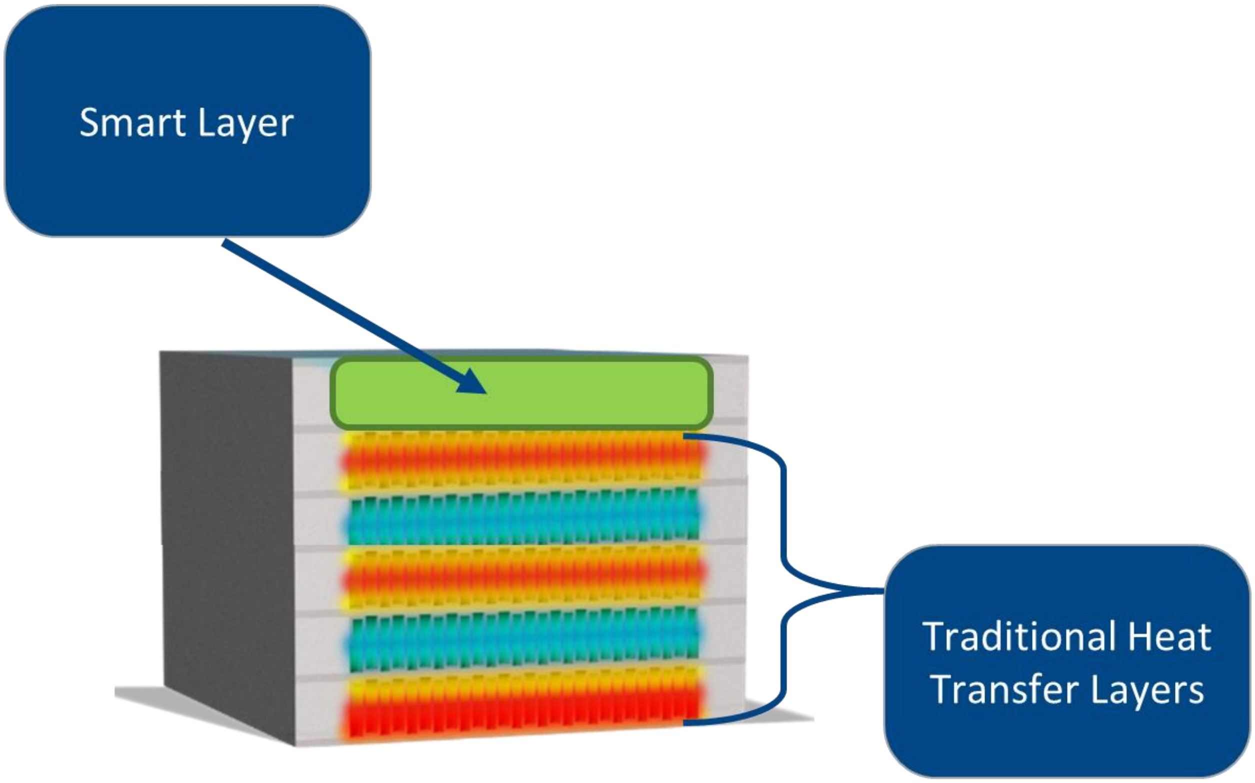

Figure 5: Smart Layer replaces outside dummy layers

Smart Layer is a system of specially designed inactive layers located on the outside of the core block that are charged with nitrogen. By monitoring the charge pressure while the BAHX is in operation, an operator can determine if any cracks have formed in the outside parting sheets or cap sheets. A fatigue crack in the outermost parting sheet would cause the Smart Layer pressure to rise to the pressure of the adjacent active layer, and it would prevent any external leaking of the process fluid by containing it within the Smart Layer. A crack in the cap sheet would be indicated by a drop in Smart Layer pressure. This would only allow the inert Smart Layer nitrogen charge to leak to atmosphere. In either case, Smart Layer alerts the operator that fatigue damage has occurred. Since there is no loss of containment, no emergency shutdown is required. This allows the owner time to plan an orderly repair and assess plant operations to discover the root cause of the fatigue on their preferred schedule.

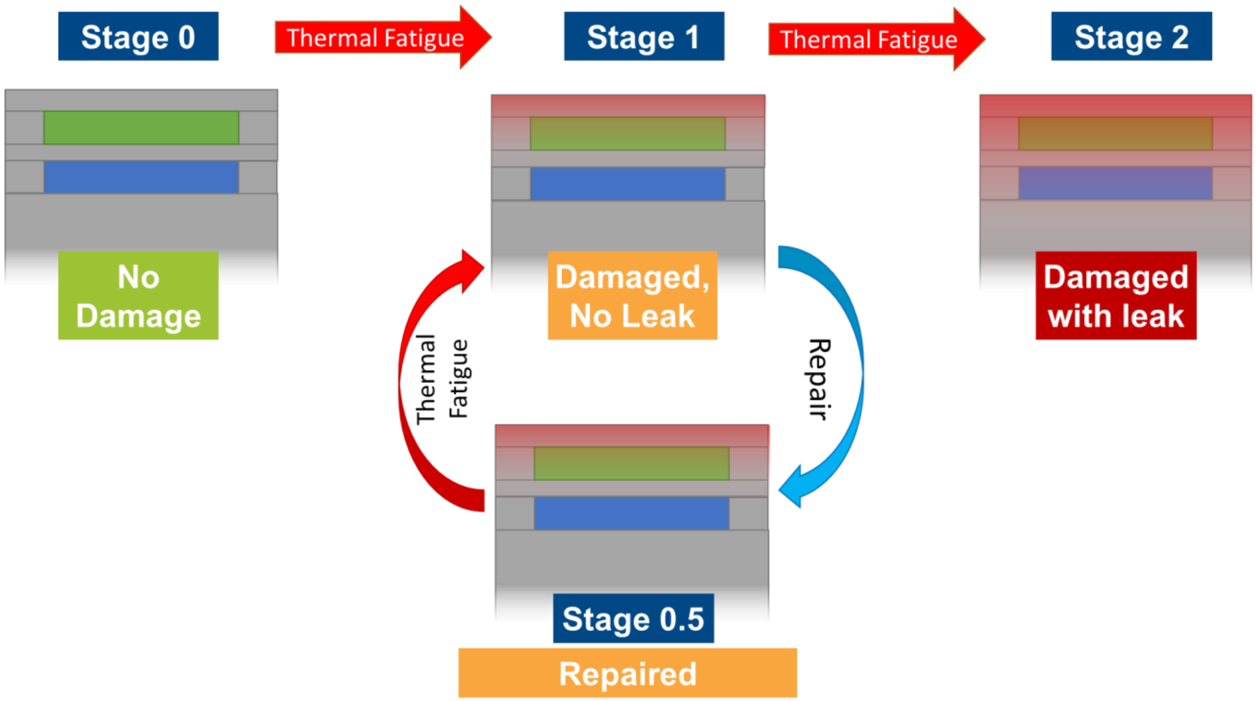

Figure 6: Smart Layer indication stages

Thermal fatigue damage can occur under operating conditions that exceed Chart's thermal guidelines, such as during frequent transient events, constant temperature cycling, or unstable flow. This damage occurs preferentially in the outer sheets. When a critical threshold of damage has occurred, a sheet crack will develop, and the Smart Layer will advance from Indication Stage 0 to Stage 1. The first crack will result in a Smart Layer indication, alerting operators that thermal fatigue damage is occurring prior to the occurrence of any external leaks. At this point, the owner should review their operating data and schedule a repair, but they may continue to operate.

After repairs, the unit is now in Stage 0.5; there are no external leaks, the Smart Layer functionality is restored, the unit is returned to operation, but it is likely that residual fatigue damage exists in the unit. If no changes to operations were made, the same conditions that caused the initial Smart Layer indication are likely to cause thermal fatigue damage to continue to accumulate until another indication occurs, returning the BAHX to Stage 1. The owner may repair the heat exchanger a second time, but Chart recommends installing a new BAHX after a second repair. If operations continue in the Stage 1 condition for too long, the damage may progress until an external leak is formed at Stage 2. At this point, the owner must remove the unit from service until repair or replacement can be made.

Relevant commentary is provided by the ALPEMA 4th edition:

> *To achieve maximum life expectancy of the heat exchanger, root cause analyses of leakage/failure events should be conducted. This may involve metallurgical analysis and/or review of past operating history. If thermal fatigue is suspected as causing the leaks and the repair under consideration is the second repair due to thermal fatigue, it is recommended the customer replace the heat exchanger within a reasonable time frame.*

Additional commentary by the GPA Technical Bulletin of Brazed Aluminum Heat Exchangers, GPA-TB-M-001:

> *Consider replacing a heat exchanger within a reasonable amount of time if analysis of historical operating data shows that thermal fatigue contributed to the leak, and especially if the heat exchanger requires a second leak repair due to thermal fatigue.*

Smart Layer Difficulties

One of the difficulties of Smart Layer involves the pressure relief system. The current implementation of Smart Layer contains a pressure relief valve (PRV) dedicated to the Smart Layer. Most users select to vent the pressure relief outlet to a common flare. This involves careful sizing of the PRV and installation of additional discharge piping.

Another difficulty is the charge pressure in the Smart Layer must be monitored and operators must be trained to recognize a Smart Layer indication. This involves patching into the plant distributed control system (DCS) and periodic training and equipment maintenance.

Smart Layer Use Cases

Smart Layer has been successfully deployed in many plants, but it is most effective in locations that have a history of diminished BAHX life expectancy. Applications where BAHX have operated for 40 years without incident will likely not benefit from the additional costs associated with Smart Layer equipped units. However, there are plants where BAHX have a history of developing leaks well before typical service life is reached. In these instances, the value of advanced warning of fatigue damage and expense of unexpected plant shutdowns can greatly outweigh the costs of Smart Layer.

The inclusion of Smart Layer on a BAHX will not shorten the life expectancy of the unit. It also will not prevent continued rough service after an indication from developing into a leak if operated long enough in the Stage 1 condition. It will, however, provide an opportunity to continue operating for a limited time until repairs can be organized, and process control improvements made.

Conclusions

Fatigue in BAHX has long been a topic of interest in industry. Prediction of fatigue relies on computer models and many assumptions. The uncertainty inherent in fatigue data limits the value of applying fatigue predictions to field units. However, simulations have proven valuable in predicting relative impact of different scenarios on BAHX fatigue life and have been successfully used in HAZOP studies and in process improvement efforts.

Detection of fatigue in field units has not been practical until recently with the introduction of Smart Layer technology. This system captures the first fatigue crack of a unit and prevents it from causing an external or cross-pass leak and alerts operators. However, there are costs associated with installing and maintaining Smart Layer in the field. Both fatigue prediction by simulation and fatigue detection by Smart Layer have distinct roles in promoting effective use of BAHX.