White paper

How to minimize fatigue problems in plate-and-shell heat exchangers

Increase uptime in positions with fluctuating temperatures or pressures

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Executive summary

Plate-and-shell heat exchangers have become very popular over the last decades thanks to their high thermal efficiency, compact size and ability to withstand high pressures.

However, many companies have discovered that this type of heat exchanger is sensitive to metal fatigue. In this white paper, we show that fatigue problems can be avoided with good design and manufacturing practices.

To avoid fatigue problems, you should pay particular attention to the following factors when investing in a plate-and-shell heat exchanger:

- Plate design. Make sure the design of the plates does not cause unnecessary stresses on the welds and plates.
- Here too. The plates must be supported in an optimum way.
- Welding technique. The plates should be laser welded and not plasma welded. Laser welding produces a stronger joint of higher quality that is less susceptible to fatigue.

Please contact us if you have any questions or if you would like to discuss the benefits of plate-and-shell heat exchangers.

1. Introduction

Plate-and-shell heat exchangers combine the exceptional heat transfer efficiency of plate heat exchangers with the ability to handle high pressures found in shell-and-tube heat exchangers. This has made them the preferred choice for a variety of heat transfer duties in many industries.

These duties often include high, fluctuating temperatures and/or pressures, which can cause material fatigue. The heat exchangers are often process critical, and it is essential to do everything to avoid fatigue-induced failure.

Unfortunately, most conventional plate-and-shell heat exchangers are designed and manufactured in a way that leads to unnecessary problems and equipment breakdown.

In this white paper, we will discuss these problems and how they can be avoided. You will learn about the critical factors to consider when investing in a plate-and-shell heat exchanger in order to minimize the risk of unplanned downtime.

Figure 2.1 Two airplane crashes in the early 50s are tragic examples of the effects of metal fatigue. The de Havilland DH 106 Comet was the world's first commercial jet airliner, and shortly after its introduction in 1952, three Comets broke up in mid-air with devastating consequences. The investigation showed that two of the crashes were caused by metal fatigue.

The Comet featured large, rectangular windows. High stress at the corners, in combination with bad installation methods, caused fatigue cracks that eventually led to the fuselage breaking apart.

The airplane was quickly taken out of operation and redesigned. Part of the redesign was the introduction of oval windows, a standard followed by all airplane manufacturers ever since.

2. Fatigue

Material fatigue is the most common reason for failures in mechanical structures. It occurs when a machine part is exposed to loads that vary cyclically over time, causing it to break at stress levels that would be safe under static conditions.

Fatigue failures happen suddenly and without obvious prior warning signs such as deformations. This makes them very hard to predict and can lead to serious accidents.

An example is railroad axels that are subjected to cyclic loads due to their rotation. The stress acting on the axel can be well below the yield stress and it can perform as planned for a long time – and then it suddenly breaks without warning.

Logarithmic relationship

Train accidents due to broken axels were common in the early days of rail traffic and led to the first investigations into the nature of fatigue by German engineer August Wöhler.

He discovered a logarithmic relationship between the load that a machine part can endure and the number of load fluctuations before a break will occur. This is shown in figure 2.2 where the stress (S) is plotted as a function of the logarithm of the number of load cycles to failure (log N).

The logarithmic nature of the relationship means that the lifetime of a component increases dramatically with even a minor decrease in stress. Design changes that reduce stress can therefore have a significantly positive effect on the lifetime of a component.

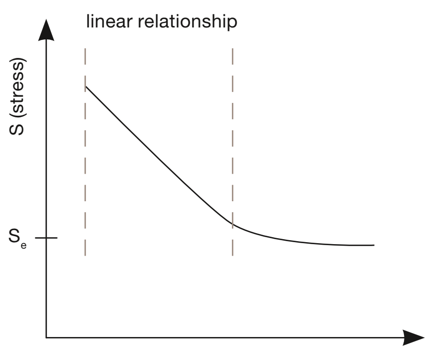


Figure 2.2 An S-N diagram or Wöhler diagram shows the relationship between stress and the number of load cycles to failure. For stress levels above the so-called endurance limit (S_e), the relationship is logarithmic. This means that even small changes in stress level have a big impact on the lifetime of a component.

Causes

Small cracks are the starting point for fatigue failures. These cracks can be caused by defects such as slag entrapments, pores, undercuts or small surface cracks, but they can also arise where no visible defects are present.

Crack formation in homogenous machine parts is caused by defects in the atomic structure called dislocations. A dislocation is an atomic plane that ends in the middle of a steel grain, instead of traversing it (see figure 2.3). These dislocations cause stresses in the grain and when the part is exposed to external loads of sufficient magnitude, the shear stresses will cause the disloca-tions to move. If the dislocations gather at grain boundaries or slag inclusions, they will eventually form microscopic cracks.

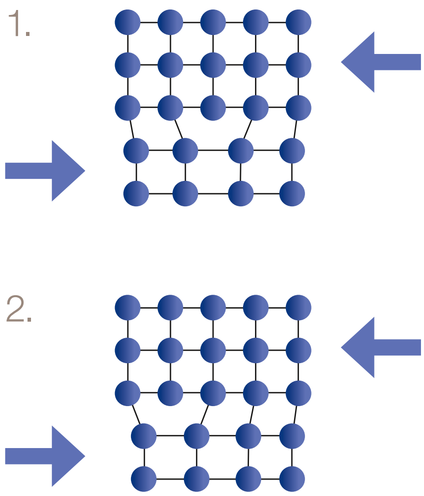


Figure 2.3 A dislocation is an atomic plane that ends in the middle of a steel grain. When subjected to shear forces that are high enough, the atomic bonds switch and the dislocation moves to the next atom plane (cf. illustrations 1 and 2 above). This continues until the dislocation reaches the grain border. When enough dislocations have gathered, a microcrack has been formed. This is a perfect starting point for fatigue cracks.

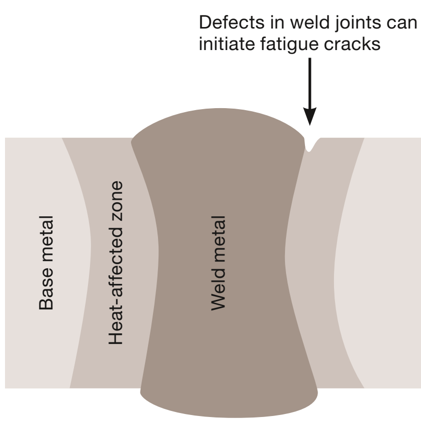


Figure 2.4 The weld seems are the most sensitive parts of a welded structure in regards to fatigue. Defects such as pores, undercuts and entrapments are common starting points for fatigue cracks. To avoid unplanned downtime, it is therefore crucial to choose heat exchangers that have been manufactured according to the highest quality standards.

The tips of the cracks are stress concentrations, and the crack will continue to grow with every load cycle. Eventually the crack becomes so large that the remaining area of the part cannot support the load and it fractures.

Stress concentrations

Stress concentrations cause fatigue cracks. Identifying stress concentrations during the design phase is therefore crucial in order to minimize fatigue. By redesigning the part, the load can often be distributed over a larger area and the stress is reduced. In some cases, a redesign can eliminate stresses altogether, as we shall see in section 4.

Even small reductions in local stress cause significant increases in fatigue resistance because of the logarithmic relationship between stress and the number of load cycles.

Weld joints

A second cause is that the welding process causes residual stresses due to the heat treatment of the material. These residual stresses are strongest in the areas that have been heated the most, and they add to the external load. This raises the average stress level in the component, which can severely reduce the weld's fatigue resistance.

The heating of the material when welding high carbon or alloy steels also causes the crystalline structure of the steel in the weld metal and the heat affected zone to undergo a transition to a much harder and more brittle form called martensite. This reduces the elasticity of the material and its ability to withstand fatigue.

Choosing the optimal welding technique is critical for fatigue resistance. To maximize equipment uptime, one must ensure high weld quality to avoid defects and minimize the amount of heat going into the weld area to reduce residual stresses and brittleness.

3. Fatigue in welded heat exchangers

Figure 3.1 Conventional plate-and-shell heat exchangers subjected to high, varying temperatures and pressures often have problems with leakages around the port holes due to material fatigue. A few, seemingly small, design improvements can eliminate this problem.

Many heat exchangers operate under conditions with cyclically changing temperatures and pressures, causing fatigue problems. The nature of the fluctuations has a big impact on the service lifetime of the heat exchanger, and there are many variables influencing the speed of the fatigue process:

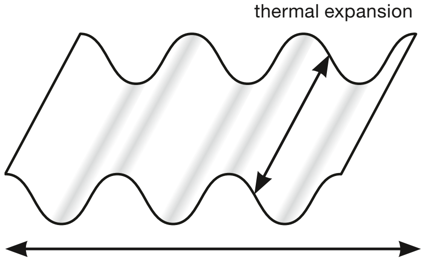
- The amplitude of the fluctuations
- The frequency of the fluctuations
- The base stress level
- Whether the variations are an issue of temperature, pressure or both.
- The design of the heat exchanger and the magnitude of the peak stresses
- The quality of the welds

The best way to reduce fatigue problems is to examine the entire process and try to optimize it from a fatigue point of view. Is it possible to reduce the amplitude of the cycles? Is it possible to avoid sudden starts and stops?

A key question is the type of heat exchanger being used and if it has been designed to withstand fatigue. Small design improvements can have a large impact on fatigue resistance, and choosing the right model can make a big difference for plant uptime.

4. How to design plate-and-shell heat exchangers for minimal fatigue

Plate-and-shell heat exchangers have become a popular alternative to shell-and-tube heat exchangers thanks to their high thermal efficiency and compact size. But many plant engineers have learned the hard way that fatigue resistance in a conventional plate-and-shell is poor. The reason for this lies in the way they are designed.



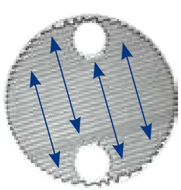


Figure 4.1 The corrugation of the plates in a conventional plate-and-shell heat exchanger gives the plates different mechanical properties in different directions.

Problem 1 – the conventional plate pattern

To maximize heat transfer, the plates in a conventional plate heat exchanger are corrugated to increase turbulence in the channels. The corrugation gives the plate different mechanical properties in different directions and causes expansions and contractions to predominantly take place in one direction (the weaker of the two), see figure 4.1.

The plate pack is comprised of two types of plates with the corrugation pattern running in different directions. Alternating between the two plate types further increases turbulence. But it also means the plates are pushed in different directions when changing operating temperatures or pressures, which causes them to expand and contract, see figure 4.2.

This puts high, alternating stress on the plates and welds, quickly leading to fatigue failure. The most common place for collapse is in the welds at the area of the portholes where stress is greatest.

Solution

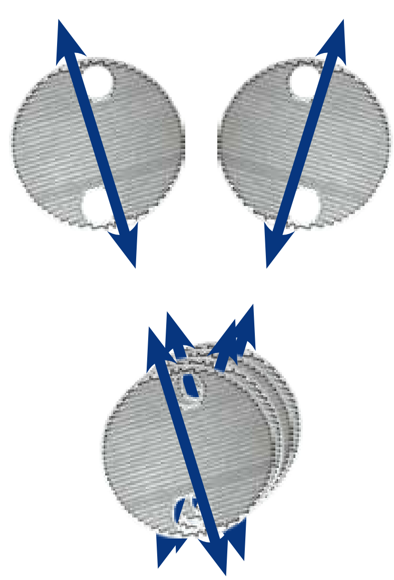


Figure 4.2 To increase turbulence, the corrugation patterns of the plates in a conventional plate-and-shell heat exchanger go in two directions.

Every second plate in the plate pack is corrugated in the same direction, causing adjacent plates to pull in different directions during operation. These added stresses quickly cause fatigue failures if the temperature and/or pressure varies over time.

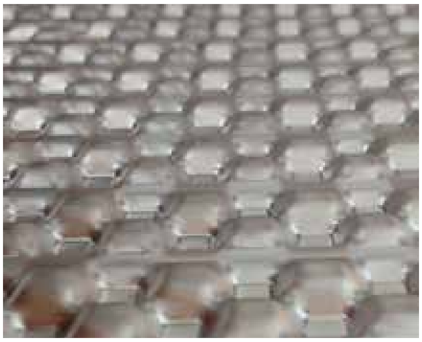


Figure 4.3 The unique rollercoaster pattern found on the plates in Alfa Laval's DuroShell plate-and-shell heat exchanger gives the plates identical mechanical properties in all directions. This eliminates unnecessary stresses caused by the plate pattern and increases fatigue resistance.

Figure 4.4 In a conventional plate-and-shell heat exchanger, the plates are compressed between the two thick end plates. The plate pack is kept together by rods on the outside of the pack, and the inlet and outlet tubes are welded to the first plate in the pack. This is a design with many inherent problems and with limited resistance to fatigue.

Figure 4.5 In Alfa Laval's DuroShell heat exchanger, the inlet and outlet tubes transverse the entire plate pack, adding strength where it is needed most. This design combats fatigue problems and improves the flow distribution, which in turn increases heat transfer efficiency.

The best way to combat fatigue is to design for minimal stress. When Alfa Laval's engineers designed the DuroShell plate-and-shell heat exchanger, they decided to eliminate the extra stress caused by the corrugation pattern.

The solution was to create a new plate pattern that has equal thermal expansion and mechanical strength in all directions. This patented pattern consists of bumps and depressions that are distributed so that thermal expansion and plate stiffness are identical in all directions.

As a result there are no stress concentrations in the port areas, which significantly improves resistance to fatigue.

Problem 2 – mechanical strength

In a conventional plate-and-shell heat exchanger, the plate pack is kept in place by steel rods that have been welded to the thick end plates. This is done to minimize the extra stress in the heat transfer plates caused by the corrugation pattern. However, the steel rods have little supporting effect on the plates since they are on the outside of the plate pack.

A second issue is that the inlet and outlet tubes only go as far as the first heat transfer plate. The tubes are welded to the first plate, meaning the connecting welds are subjected to high loads and run a high risk of failure.

Solution

When designing the DuroShell plate-and-shell heat exchanger, Alfa Laval's engineers made double use of the inlet and outlet tubes and let them reinforce the entire heat exchanger.

Instead of terminating them at the ends of the plate pack, the inlet and outlet tubes run through the entire heat exchanger. This strengthens the plate pack considerably and eliminates the need for external rods.

The inlet and outlet tubes are only welded to the thick end covers enclosing the entire plate pack, and not to the thin heat transfer plates, which ensures minimal stress.

Figure 4.6 Laser welding is a much more exact technique than plasma welding and does not heat the stainless steel plates nearly as much. The result is a better and stronger joint that is less susceptible to fatigue.

Problem 3 – weld quality

As described in section 2, welds are the weak points in a heat exchanger operating with varying temperatures or pressures. Fatigue cracks almost always start in the heat-affected zone or weld material, making the choice of welding technique crucial.

Solution

The most common techniques used for manufacturing heat exchangers are plasma and laser welding. Laser welding is by far the best option in terms of fatigue resistance.

When bonding two plates using laser welding by transparency, one plate is placed on top of the other and a narrow laser beam melts the two plates together. The amount of heat going into the metal is only about a third compared to plasma welding, resulting in a weld of much higher quality.

The benefits of using laser welding compared to plasma welding include:

- Fewer defects that can act as starting points for fatigue cracks.
- The heat-affected zone is much narrower, meaning more of the material keeps its original properties and strength
- Fewer residual stresses
- More consistent weld seams

The results are twice the thermal fatigue resistance and up to four times better endurance to pressure-induced fatigue

Figure 4.7 Lab tests of Alfa Laval DuroShell.

The combined result

When combining the benefits from a better plate pattern, extra mechanical strength and laser welding, the outcome is very good. When testing the Alfa Laval DuroShell – where all these improvements have been implemented – the results are twice the thermal fatigue resistance and up to four times better endurance to pressure-induced fatigue than a conventional plate-and-shell heat exchanger.

5. Summary

Plate-and-shell heat exchangers offer benefits such as:

- High temperature and pressure durability
- Compact size and low weight
- High thermal efficiency
- Low pressure drop
- Great flexibility
- Exceptional heat recovery abilities

Unfortunately, conventional plate-and-shell heat exchangers have problems with fatigue in duties where the operating temperature or pressure varies. But, as we have shown in this white paper, this problem can be eliminated if the heat exchanger is designed and manufactured according to the following three principles:

1. The plate pattern must not cause unnecessary extra stress on the plates and welds. Avoid the traditional corrugation pattern.
2. The heat exchanger should be designed so that the plate pack is supported as much as possible. Using inlet and outlet tubes that transverse the plate pack is an effective way to achieve this.
3. The plates should be laser welded and not plasma welded.

If you take the above points into consideration when investing in your next plate-and-shell heat exchanger, you can expect long, trouble-free uptime.

6. Contact Alfa Laval

If you have any questions or would like to discuss heat exchangers for you plant, please contact us. You can find contact information for your nearest Alfa Laval representative on our web site: www.alfalaval.com.

We look forward to hearing from you.

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Our equipment, systems and services are dedicated to helping customers to optimize the performance of their processes. Time and time again. We help our customers to heat, cool, separate and transport products such as oil, water, chemicals, beverages, foodstuff, starch and pharmaceuticals.

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