Fatigue is, and most surely always will be, a very common cause of failure in industrial machinery such as pumps. Engineers on plant sites should know the basic facts about this type of failure and the type of loads that cause it in order to recognize such failures and take steps to reduce their occurrence. In this first of a short series of articles, Here, Rafael Ocampo revisits the basic theory concerning fatigue.

Some theory

In actual machine parts, cracking usually starts at a surface or subsurface discontinuity, such as a scratch, keyway, fillet, hole or inclusion, any of them having more or less a notch effect that locally increases the stress. This is a reality frequently forgotten by field engineers when specifying, designing, machining or using spare parts manufactured on site.

Usually the designer specifies a certain detail – e.g. a fillet radius – but the machine workshop sometimes makes it smaller, or is careless and leaves some other stress raiser that the designer did not intend. Such instances have to be watched very carefully by field maintenance engineers. It would be a good practice to investigate, during specification before manufacture and during final inspection after manufacture of all parts made on site, if there is any stress concentration point that can (and should) be eliminated.

Famous design academic Virgil Faires stated: “As changes of sections and other discontinuities in

Figure 1. Diagram of fatigue failures (modified from reference 2). The shaded areas indicate the zones of brittle fracture.
general can occur in an infinite variety of ways, it is not always possible to find a stress concentration factor that applies to the calculation of the case at hand and the exercise of judgement with considerable estimation is often essential. This is a clear indication of how difficult it can be to design an apparently simple spare part successfully and how easy it can be to produce a poor design that will experience a fatigue failure in service without warning.

The effect of the design forms of machine elements on their endurance limit is represented in calculations by the stress concentration factor \( k_\sigma \) (for normal stresses) or \( k_\tau \) (for tangential stresses), defined as the proportion of the limit of endurance for a smooth sample over the limit of endurance for a sample of the same size but containing a stress concentration point. There are many tabulated values for these coefficients but it is not always possible to find exactly the required one.

Bending and torsion are the stress patterns most frequently found in machine elements, because many of them rotate under radial loads or rotate while transmitting torque, or both. With identical stress concentration points, \( k_\tau \) is smaller under pure cyclic torsion than \( k_\sigma \) under bending or tension–compression, and thus stress raisers are less harmful in parts subjected to pure torsion than in those subjected to bending or combined loads. Under rotating bending loads, the fracture generally occurs on a surface that is perpendicular to the rotation axis, regardless of whether the load is high or low.

The appearance of the fracture surface in different cases will present features that can give an indication of the type of load and the presence of a stress raiser. The ductile and brittle zones of the fracture will be smaller or greater according to the value of the load and the form of these two zones will also vary according to the presence of small or large stress raisers, as shown in Figure 1 (ref. 2). Figure 2 shows an unusual fatigue fracture, while Figure 3 shows the surface appearance of a fatigue fracture in which the ductile and brittle zones of the fracture are clearly manifest. Both these cases will be discussed in the second and third parts of this series, respectively. Under cyclic twisting, fatigue failures may occur:

- On the surfaces at 45° to the torsion axis, on which the maximum normal stresses act, under low cyclic overload.
- On the plane perpendicular to the axis, where the maximum tangential stresses operate, under significant cyclic overload.

Failure of machine elements under alternating stresses occurs at stress values below the ultimate strength and also below the yield point if the variations of stress are repeated often enough. For this reason, fatigue failures of parts, even those made from plastic materials, do not usually involve any external manifestation of plastic deformation and the breakage occurs suddenly, without prior hint that a failure is going to occur.

As corrosion mainly affects the exposed surface of machine elements, and fatigue failures generally begin at the surface, protection against corrosion is a very important issue when designing parts subjected to alternating stresses. The reduction of fatigue strength in corrosive media is considerable, so careful selection of the material is of the highest importance. Some authors state that the limit of endurance of ordinary structural steel in fresh water is half that in air, and in sea water is a quarter of that in air, at the test base of 10⁶ cycles.

**Methods to increase fatigue strength**

The form of machine elements is of special importance. From this point of view, the design should satisfy two main requirements. Firstly, the form of a component should ensure such a direction of force flux as to make the largest possible volume of the component bear the load. Secondly, the form of the component when assembled with other elements of the unit should ensure the transmission of the load over the entire designed contact surface and over it alone. From these two main requirements,
certain general design principles can be formulated.

Avoid abrupt changes

Abrupt changes of form should be avoided. This is very important since abrupt changes of cross section induce a considerable stress concentration, affecting the endurance of the component when subjected to alternating stresses. The magnitude of the stress concentration factor depends not only on the form of the transition curve but also on the ratio of the dimensions of adjacent cross sections. Abrupt changes in these dimensions increase the local stress.

Equal strength

The component should be so designed as to ensure as far as possible equal strength in all its cross sections. Such a design would be the most economic; however, it is frequently very difficult to achieve from a production point of view. Larger dimensions increase strength under static loads but under alternating stresses the increase in size may have the reverse effect and reduce the margin of safety. The effect of the absolute dimensions of a component on its strength is as follows: as the size of the cross section increases, the limit of endurance decreases.

Stress relief

To achieve a better force distribution pattern, the forces should be directed away from the stress concentration points. An effective practical way is to introduce additional, smaller concentration points functioning as stress relieving points for a larger stress raiser. Such cases include the relieving grooves machined on both sides of a heavy notch, recessed fillets, etc.

Optimal surface

As any fatigue damage begins in or near the surface, it is important to reduce to a minimum the stress concentration points of any type on the surface.

Summing up

Field engineers should learn to interpret the appearance of fatigue fractures in order to recognize the causes and conditions that initiated them. However, it is even more important to be prepared to avoid the occurrence of such failures. Many decisions taken when designing, manufacturing or repairing pump parts could lead to fatigue failures if the possible introduction of stress raisers is not very carefully checked.

It is essential to keep in mind the basic theory concerning fatigue failures if a safe and reliable machine element is to be designed and manufactured. Although it is not always carried out, a very careful final inspection of parts manufactured on site will uncover harmful details. The practical skills acquired through years of experience will be essential to recognize and remove what could be a weak point from the fatigue standpoint.

So far, several of the basic important elements to be taken into account relating to fatigue design have been revisited in order to recall some relevant aspects that will help to achieve a better understanding of the behaviour of real machine parts. To exemplify this behaviour, some real failures will be discussed in several case studies to be presented in the following articles in this series.

References


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