Batch centrifuge basket design

1. Abstract

A short overview of batch centrifuge basket design is presented with reference to process performance, efficiency, perforation type, safety and cost. The mechanical loads supported by the basket during normal and out-of-balance operation are discussed. Aspects such as basket perforation type, welds, the use of reinforcing hoops, materials of construction and fatigue life are also considered. The requirements for on-going inspection and maintenance of baskets are emphasised

Keywords: centrifuge, centrifugal, basket, design, fatigue, maintenance, inspection

2. Introduction

The design of centrifuges used within the European Economic Area is subject to the requirements laid down in the harmonized Type C standard EN12547-2014 “Centrifuges – Common safety requirements” [Ref 1]. This standard covers many aspects of centrifuge design however a large part relates to the safety requirements, protective measures and verification of mechanical hazards associated with the rupture or ejection of parts from the rotating centrifuge basket. Given the potential risks associated with a poorly designed centrifuge basket this focus on safety and protective measures is understandable and consequently Broadbent manufacture all baskets to exceed the EN12547 standard regardless of their final location.

Figure 1 shows an example of a batch centrifuge. The drive motor (1) is directly connected to the basket (3) via the spindle (2). The whole rotating element of the centrifuge comprising motor, spindle and basket is supported on bearings (4) which are themselves supported by a flexible rubber cone or suspension buffer (5) mounted in the centrifuge support frame (6). The outer casing (7) is static, encloses the basket and forms part of the centrifuge supporting structure. During operation any unbalance in the load within the basket causes out of balance forces that rotate with the basket. The resulting vibration is isolated from the supporting structure (6, 7) by the suspension buffer (5).

A typical batch centrifuge used for sugar production with a basket capacity of 1.75 tonnes of massecuite per charge has a stored energy of approximately 8 MJ when spinning at 1100 RPM. This is equivalent to a 1.5 tonne car travelling at 370 km/h (230 mph). If this energy were to be released in an uncontrolled way a significant amount of damage is inevitable with possible fatal injury to individuals close at hand. It is a common misconception that the outer casing of a sugar batch centrifuge (item 7 figure 1) will contain a basket that ruptures; to have a reasonable chance of containment the outer casing would need to be in the region of 20-30mm thick.

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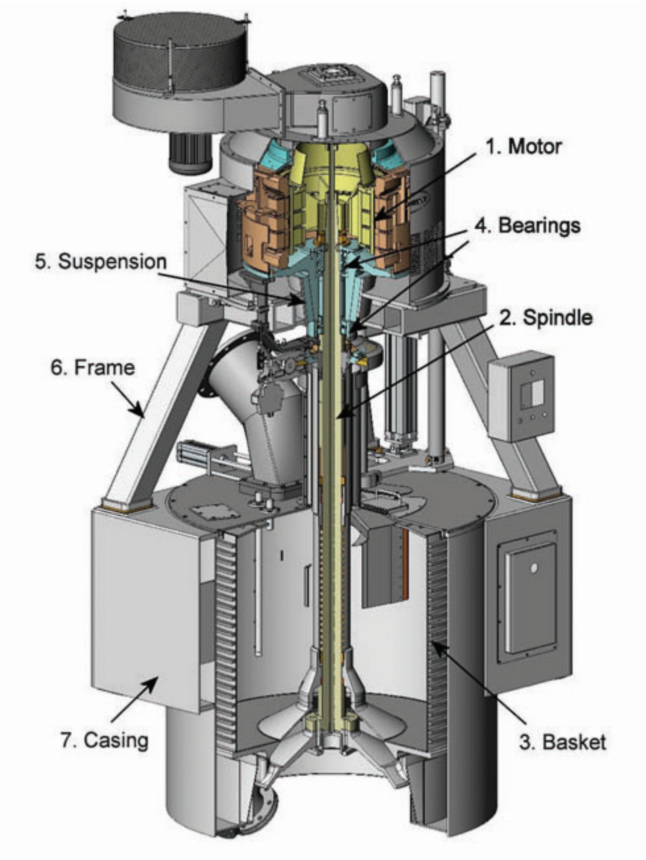
Figure 1: **Sectional arrangement of a batch centrifuge**



In addition to the obvious need for safety there are also requirements for good process performance, high reliability, low basket cost and high throughput and energy efficiency. Any final design is a balance of these generally competing requirements – with the overriding requirement being safety.

The high throughput of batch centrifuges used in the sugar industry poses an additional problem for designers. The excellent filterability of good sugar massecuite allows centrifuges to operate with fast cycling rates of 20 to 30 cycles per hour. Typically centrifuges operate for 4000 to 7500 hours per year so over an assumed life of 20 years the centrifuge basket will experience 1.5 to 4.5 million process cycles, which in turn means the designer must guard against catastrophic failure from metal fatigue caused by the cyclic stresses experienced by the basket.

Figure 2: **Photographs of typical baskets**


(A) With reinforcing hoops
(B) Plain shell without reinforcing hoops

3. Design procedure

A good understanding of the loads encountered by the basket (figure 2) during operation is a necessary first step in the design process. The basket is subjected to a variety of loads during operation and full analysis requires a detailed investigation of all possible loads. In this short overview some aspects of the following loads are considered:

- Loads due to centrifugal force acting on the self-weight of the basket.
- Loads due to centrifugal force acting on the product in the basket (i.e. massecuite).
- Loads due to centrifugal force acting on any unbalance within the basket.

3.1 Centrifugal loads due to the self-weight of the basket

The loads on an empty basket are due solely to the self-weight of the basket. If any residual stresses in the basket material are ignored then the stresses in a stationary basket are very near zero. Once the basket starts to rotate the centrifugal load on the basket structure is supported by a circumferential stress S in the basket wall (comprising shell plus hoops if fitted) which is related to basket diameter D and centrifugal acceleration or G (where 1G = 9.81m/s2) by Equation 1:

$$S \text{ is proportional to } G\,D \qquad (1)$$

This shows that for a given G, the basket circumferential stress S increases linearly with basket diameter D and this has the effect of limiting the maximum diameter of a basket. Typically approximately 50% of the allowable maximum stress levels in the basket wall (shell plus hoops if fitted) are taken up supporting the basket self-weight, leaving the remaining 50% to provide support for the massecuite load within the basket. The larger the basket diameter the greater proportion used to support the basket self-weight leaving less to support the massecuite.

3.2 Centrifugal loads on the basket from the product

The addition of massecuite in the basket increases the mass to be supported and therefore adds to the stress in the basket wall. Centrifugal acceleration develops hydrostatic pressure within the sugar massecuite in the basket similar to that in a liquid giving a parabolically increasing pressure distribution as shown in figure 3. This pressure is supported by an additional circumferential stress in the basket wall. In the middle section of the basket, this stress is simple to calculate using standard pressure vessel formulas and is proportional to the total mass of product. When considering the pressure on the top and bottom of the basket, the particulate nature of the product must be considered. A pile of solid particles resting on the floor settles to form a cone due to internal friction effects. Similar effects occur in a rotating basket but in this case the ‘gravity’ is horizontal and the restitution surface is indicated in figure 3 by a dotted line: The material below the line is supported by the basket shell while the ‘wedge’ of material above the line is supported by the basket top.

As already discussed, the stress in the waist of the basket is mainly circumferential tension with a small axial tension due to the lateral upwards pressure on the top and bottom. The situation at the top and bottom of the basket is more complex. The upward pressure on the top produces bending stresses around the corner of the basket where the shell joins the top disc. Conversely, the top acts as a stiffener to restrain deformation of the shell. Similar factors apply at the bottom of the basket. The net result is that the circumferential stresses in the shell at the top and bottom of the basket are lower than at the centre portion but there are significant axial bending stresses which may be very high inside the corners. This is illustrated in figure 4 which shows the axial stresses and (magnified) deformations in a segment of the top half of a typical basket at spin speed.

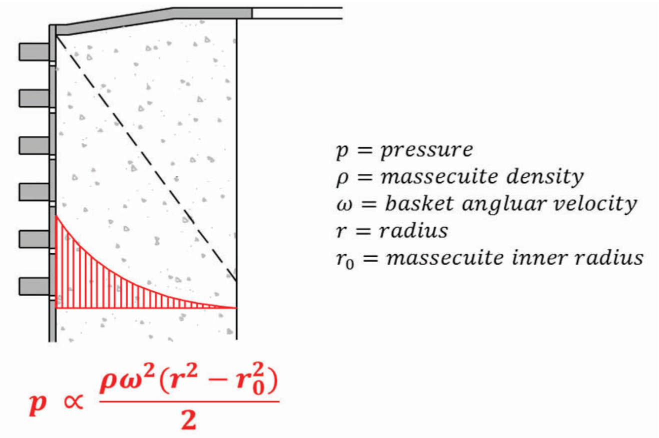


Figure 3: **Pressure distribution on basket top**

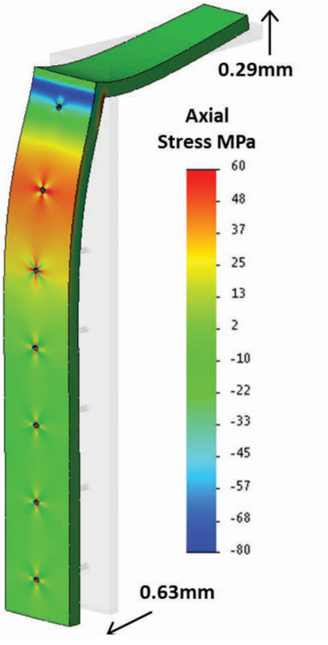


Figure 4: **Deformation (100x actual) for typical plain shell basket**

3.3 Unbalance forces on the basket

Most types of centrifuge incorporate a means to reduce the transmission to the surroundings of any forces due to unbalance in the basket which are then perceived as vibration. Batch sugar centrifuges employ a pendulum suspension which allows the whole rotating assembly to swing slightly to find a better balanced axis of rotation. To minimize the background level of vibration, centrifuge components are precision dynamically balanced during manufacture.

When massecuite is fed into the basket, the resulting cake of material is rarely perfectly balanced. Although the suspension system (item 5 figure 1) reduces the transmission of vibration to the surroundings, the full forces of unbalance are active within the rotating assembly itself. It is important that the basket is designed to accommodate the stresses and deformations resulting from these out-of-balance loads. Normally the unbalance is limited to a small fraction of the massecuite load and the vibration that results if the out-of-balance limit is exceeded can be detected by the centrifuge’s instrumentation and remedial action taken automatically by the control system. Figure 5 shows the deformed shape of a basket with a 10kg out of balance at 1100 G which generates an out-of-balance force of 11 tonnes and results in a basket deformation adjacent to the out of balance of approximately 4mm. It can be seen that significantly increased stresses can occur locally, particularly bending in the basket bottom.

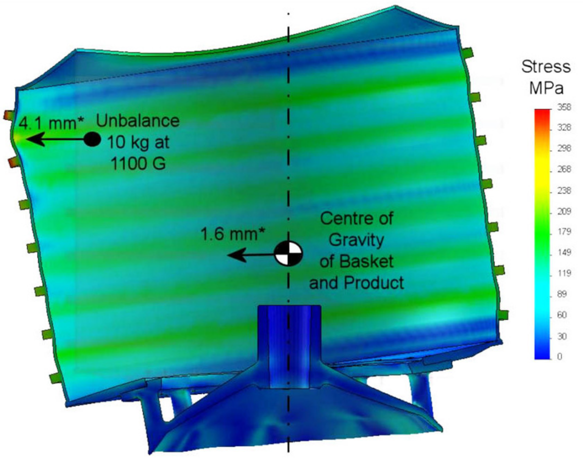
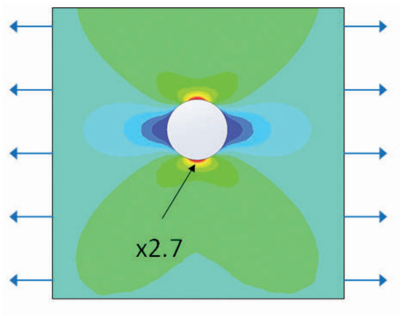


Figure 5: **Deformation (50x actual) for basket with 10kg OOB**

Figure 6: **Stress concentration due to circular hole**



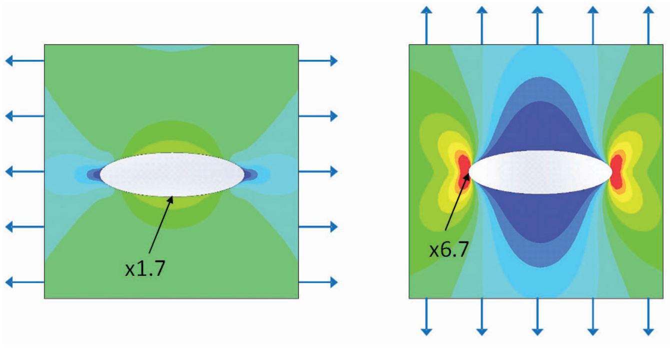
3.4 Basket perforations

A complicating factor in basket design is the need for perforations to allow the mother liquor (molasses) to drain from the centrifuged cake. As is well known, the placement of a hole in a uniformly stressed sheet of material increases the stresses local to the hole [Ref 2]. For the case of a pattern of circular holes in the shell of a typical centrifuge basket the peak stress next to the hole is around 2.7 times greater than the stress distant from the hole. This effect is shown in figure 6.

The designer must account for this increased level of stress when designing the basket, and it can be seen from figure 6 that the effect is significant. The shape of the hole has an important effect on the stress concentration factor. For a pattern of ellipses of aspect ratio 3.3:1 with the stress acting parallel to the long axis the stress concentration reduces to about 1.7 (figure 7a). However if the stress acts perpendicular to the long axis of the ellipse the stress concentration increases to around 6.7 (figure 7b). Clearly, elliptical perforations should be used with caution if the stress is not purely in one direction and aligned with the long axis such as the regions near the top and bottom of the basket where axial bending stresses are significant (figure 4).

The number of perforations is an important factor in basket design. Too few perforations may impair process performance because the massecuite purging is restricted thus limiting the throughput of the centrifuge and making the cut-off between mother liquor and washings run-off less sharp. Too many perforations may impair the strength and the basket cost is increased. The method of forming the perforation is also important. Any tearing or melting of the material during the process of forming the perforations (e.g. punching or laser cutting rather than drilling) will further increase the residual stress levels around the perforations. Drilling the perforation in a flat sheet of steel before rather than after rolling it into a cylinder to produce the basket shell also increases the residual stresses local to the perforations.

Figure 7: **Stress concentrations due to ellipse**


(A) Stress parallel to long axis

(B) Perpendicular to the long axis

Both stress concentration factors and residual stress have a major effect on the fatigue strength of the basket as discussed below in section 3.5.

3.5 Materials of construction and fatigue life

Baskets are normally manufactured from standard high strength carbon steels, austenitic or duplex stainless steel and their cast equivalents. The centrifuge standard EN12547 specifies minimum requirements for material elongation at rupture and impact energy of fracture and thus effectively prohibits the use of materials that may be very strong but brittle. EN12547 also provides details of suitable methods for calculating the stresses in the centre portion of the basket and specifies factors of safety to the tensile properties in a similar way to pressure vessel codes. This method of design only covers 'steady' (i.e. non-cyclic) loading. However as outlined in section 2 cyclic loading dominates in the sugar application and therefore design methods considering only steady loading are unsuitable.

The centrifuge standard requires that the '*rotor* (i.e. basket) *shall be designed with a safety margin against fatigue failure'* and the *'load and expected number of cycles shall be assessed to determine if this will lead to fatigue failure during the foreseeable life of the centrifuge*'. [Ref 1 section 5.2.1.1].

Given that the basket will be subjected to a million or more stress cycles during its lifetime, the requirement in the standard is clearly sensible. The basket should be designed for a long life taking full account of the fatigue properties of the materials of construction and the level of cyclic stresses expected within the basket.

The ability of a material to resist fatigue failure depends on the type of loading. For example the fatigue resistance of a given material to a reversing stress of +/-***S*** differs from a stress going from zero to 2***S***. Most published data is based on alternating +/-***S*** tests which are not truly representative of centrifuge basket loading. It is possible to estimate fatigue data from reversing stress data and also to take account of residual stress and stress concentrations such as perforations using the methods of Goodman or Soderberg [Ref 5] but in order to obtain accurate fatigue life data for a particular material it is necessary to conduct tests to ascertain the fatigue life with mean and alternating stresses representative of the loadings found in batch centrifuge baskets.

As a general rule ferrous materials will not fail by fatigue, no matter how many load cycles are applied, if the stress is kept below a certain value known as the fatigue limit or endurance strength, which for steels is typically about 50% of the ultimate tensile strength (UTS). Figure 8 shows the typical variation of reversing stress fatigue strength (S) with stress cycles (N) together with the fatigue limit for $N>10^6$ cycles.

It might be thought that fatigue could be avoided by simply using a stronger material. However as the UTS increases the fatigue limit as a percentage of the UTS drops (see figure 9) and there is no benefit in using the higher strength material with a UTS above 1200 MPa.

Figure 8: **Variation of fatigue limit with number of stress cycles**

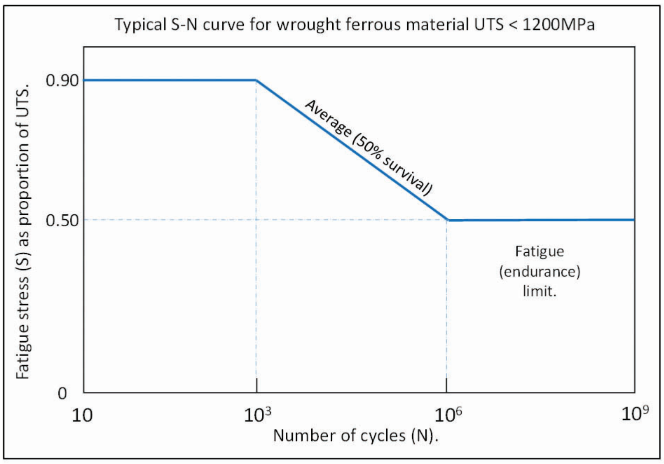
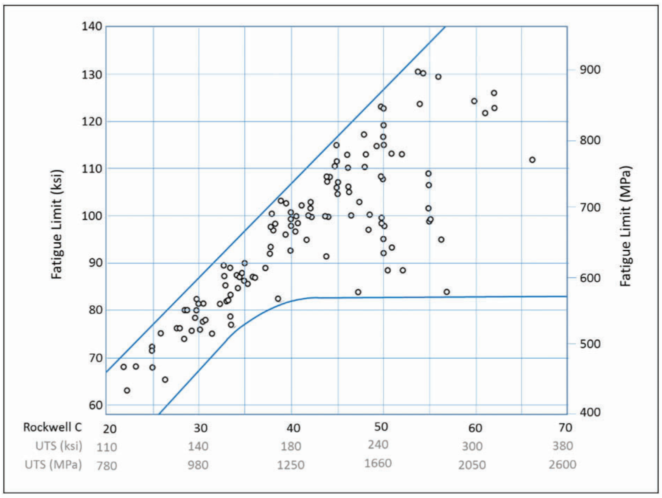


Figure 9: **Variation of fatigue limit with UTS for a wide range of steels. [Ref 3].**
Note that the x-axis is linear in Rockwell C hardness



3.6 Welds

Most basket shells are manufactured by rolling a flat plate into a cylinder and butt welding the seam together. In un-welded components, a large fraction of the fatigue life is taken up in the initiation of cracks and only a part in crack propagation. In contrast, it is prudent to assume that all welds contain tiny micro-fissures at the toe or root of the weld caused by tension during freezing of the weld metal (these do not constitute welding faults and are not detectable by non-destructive testing such as dye penetrant or radiographic testing) and so the fatigue life of welded joints is determined by crack propagation only and is significantly shorter than that of the parent material. Unlike crack initiation, crack propagation is relatively insensitive to microstructure and to mean stress which in any case is primarily the residual stress which is close to yield near welds. For these reasons it is possible to produce standard design fatigue S-N curves for various types of weld that are applicable to any steel, regardless of strength or composition. Examples are given in Ref 6. These are based on a large volume of tests on general structural steelwork but there is some evidence that these curves are somewhat conservative for welds more typical of the high quality seam welds on baskets that are carried out in more controlled conditions. Nevertheless, the evidence suggests that the operating stress in basket seam welds should be limited to levels below that acceptable in the un-welded material. This is a further reason why there is no benefit in constructing basket shells from very high strength quenched and tempered steels.

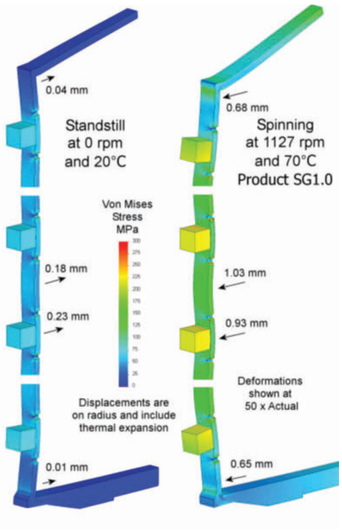
For obvious reasons, perforations should not be put through the shell seam welds.

4. Basket construction: plain shell vs hooped

There are two common methods of manufacture of basket shells (see figure 2). One uses a plain shell, the other has additional reinforcing hoops fitted to assist in supporting the shell. Both types are common in the sugar industry. It should be noted that for a basket with a plain shell (i.e. no hoops) it is the shell, with its stress concentrating perforations and welds, which must support all the loads; self-weight (section 3.1) and massecuite (section 3.2).

In the alternative case of a shell with additional reinforcing hoops there are no stress concentrating perforations or welds in the hoops and this allows them to carry higher stresses safely, thereby reducing the amount of material necessary to support the load. A typical design is shown in figure 10. As a result the hooped basket has a lower mass and inertia so requires less energy to accelerate it to spin speed.

Figure 10: **Deformation and stresses for typical hooped basket**



In general, hooped baskets can be designed with more perforations to give faster purging and combined with the lower inertia they have the potential to deliver higher throughput. They have far greater resilience against dangerous failures, as discussed below. The downside of hooped baskets is that they are more expensive to manufacture. Broadbent manufacture both hooped and un-hooped baskets (see figure 2), but for high cycling duties such as sugar production Broadbent's standard policy is to offer baskets fitted with reinforcing hoops.

In a plain shell basket, it is possible for a single crack to propagate rapidly through the whole basket giving catastrophic rupture with little warning. In contrast, it is impossible for a crack to propagate from the shell to a hoop or vice versa. Hooped baskets are usually designed to avoid immediate failure in the event of loss of one or more hoops. Likewise if the shell fails the hoops are designed to carry the total load for a short period thereby maintaining the basket integrity until the fracture is detected by the centrifuge instrumentation. Hooped baskets therefore present almost no risk of sudden failure and are the safest possible technology.

5. Maintenance and inspection

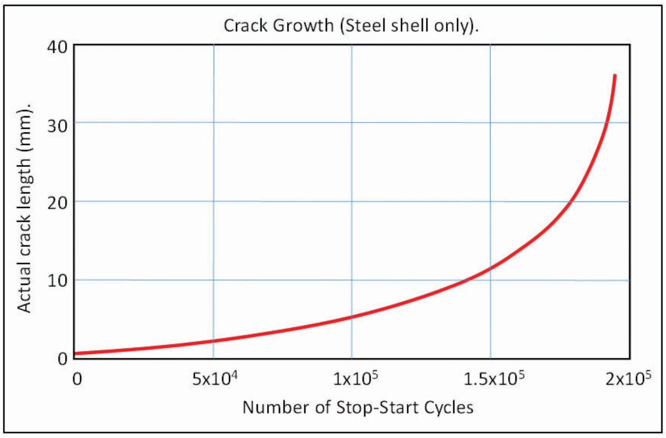
Baskets are often designed so that stresses are less than the fatigue limit and so in principle they should have infinite life. There are many baskets still in service after more than 30 years operation. However vigilant the designer and manufacturer are in their efforts to produce a basket with infinite life the possibility of failure always remains. Other than design or manufacturing problems, failure may occur due to a variety of other factors including:

- Mechanical handling damage.
- Unsuitable repairs or welding on the basket.
- Severe out-of-balance events during centrifuge operation.
- Rusting of carbon steels or general corrosion caused by chemicals used in the sugar manufacturing process (e.g. ion exchange reagents) can cause loss of material that reduces the load bearing cross sectional areas of the basket wall.
- Localized corrosion (e.g. salt attack of stainless steels in coastal regions) can initiate micro-cracking that initiates fatigue and accelerates crack propagation.

To help avoid such problems the user should always perform routine inspections on the basket and other critical components as recommended by the original equipment manufacturer. Such inspections are usually required at regular intervals, typically 12 months. Basket failures are very rare, however those few that do occur are highly likely to be the result of fatigue. It can take many centrifuge stress cycles before a crack nucleates and grows to a size where it becomes detectable, and many more cycles before it grows to the point where fast fracture occurs and the basket fails potentially catastrophically.

As part of the design process it is possible to estimate the number of stress cycle required to grow a crack from a given size to the point where fast fracture will occur [Ref 4]. If it is further assumed that inspection techniques used on the basket can reliably detect cracks of length 1mm or above then the period between inspections should be less than the time it takes for a pre-existing 1mm crack to grow to the point where failure occurs. Figure 11 shows an example of the estimated growth rate of a 1mm pre-existing crack; when the crack grows to a length of approximately 35mm fast fracture occurs and the basket fails.

Figure 11: Crack growth rates showing the number of cycle to failure



For this case it takes just under 200,000 cycles for the crack to grow to failure, which is more than 12 months operation in a sugar refinery operating 24 hours per day for 365 days per year at 20 charges per hour. So if the initial crack appeared one day after an inspection, the crack should not have grown to the failure point after 12 months, when the next inspection is due.

It is important to understand that the period between inspections (typically one year) should never be lengthened simply because all previous inspections have not revealed a problem. In fact the older a basket gets the more important the future inspections become.

6. Summary

Batch centrifuge baskets are complex items and some of the design factors are considered in the preceding sections. The key issues discussed in relation to low inertia, good process performance and long term safe and reliable operation are:

- The cyclic loading experienced by the basket.
- The stress concentrations caused by the basket perforations.
- The fatigue properties of the basket materials
- The additional safety and lower inertia afforded by the use of reinforcing hoops.
- A good understanding of the need for regular inspections and approved maintenance procedures.

Careful design, manufacture and adherence to inspection routines provide the basis for trouble free long term safe operation, as demonstrated by the many thousands of centrifuge baskets in operation in the sugar industry worldwide.

7. References

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