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Recurring Failures of a Titanium Vacuum Pump

Introduction-

A chemical manufacturing complex handling a very aggressive product was using two liquid ring vacuum pumps constructed entirely out of Titanium.

A call from the maintenance manager requesting assistance was made since the facility was spending over £10000 every six weeks on repairs to the units.

Furthermore, since the units were obsolete, the costs of maintaining the machines was spiraling as more and more parts were manufactured as "one offs".

Machinery information-

The vacuum pumps were a typical single stage liquid ring design.

All wetted components inside the machines were made entirely out of Titanium.

Titanium construction was required due to the chemically extremely hostile environment inside the pumps.

The pumps were installed as a typical duty and standby pair.

The pumps themselves were about ten years old and when maintenance was required the units had been shipped to the manufacturer for repair.

However, the manufacturer had made it known to the company that they were unable to continue to support the servicing of the units because they no longer made the pumps and in particular no longer manufactured Titanium parts.

The track record of the machines was that they had been very reliable in the past.

This put the business in a very difficult situation.

A brand new installation of two completely new vacuum pumps in Titanium from an alternative vendor was considered far to expensive. The business was not very profitable and could not support substantial investment at the time.

Additionally, the plant operated 24/7 and it was not an option to have the plant shutdown for any period of time waiting to install new pumps.

Titanium liquid ring vacuum pumps are simply not an "off the shelf" commodity meaning that any purchase and installation of new pumps would be a longer term proposition.

This meant that the only real option open to the plant was to keep the current pumps running by having parts manufactured by a third party and carrying out the overhauls themselves.

This in fact was what was happening but something was causing the increasing levels of breakdowns on the units.

Preliminary investigations-

The records kept by the maintenance department were not comprehensive, but they supported the view that the vacuum pumps had been largely trouble free apart from regular overhauls carried out by the original manufacturers.

Luckily, when the manufacturers had taken the decision to no longer manufacture Titanium parts, the stores had a reasonable stock of parts which were given to a drawing office to “reverse engineer” into manufacturing drawings for spares to be made by a third party manufacturer of Titanium parts.

Of course, what this meant was that the limits and fits of the parts had to be designed as this information was forthcoming from the manufacturer. The plant had no records or drawings of what the original manufacturing tolerances had been when the units were originally designed.

From talking to the operations and maintenance staff the following fairly consistent information was obtained.

When installed after overhaul the vacuum pumps would run quietly and smoothly for several days.

After this initial period though, the pumps would start to vibrate, gently at first but over the course of several weeks the vibration would get steadily heavier.

After about six to eight weeks the pumps would trip and be found to be seized.

There were the remnants of several failures in the plant workshop and in all cases the bore of the impeller and the shaft impeller journals were extremely heavily worn.

The wear appeared to be throwing the impeller eccentrically on the shaft and this quite obviously accounted for the steadily increasing levels of vibration as the impeller became more eccentric with time.

Exactly as described by the plant staff, the failed impellers had welded themselves axially upon contact with the end covers of the unit.

It was agreed that I would be present when the next unit was removed and stripped down.

Further investigations -

While I was waiting for the next unit to be removed for strip down I was given whatever drawings the plant had of the vacuum pumps.

Fortunately, one of the drawings was a large cross section drawing right through the centre of the unit.

What became obvious to me but I had previously missed by looking at the pump assemblies was that the bearings (one at each end) were fitted inside cartridges which were adjustable axially in housings to get the impeller end clearances central inside the casing when the pump was built up.

The bearing cartridges were adjusted axially inside the housings by the use of jacking bolts secured with locknuts.

The disadvantage of this method of securing is that it relies exclusively on friction between the locknuts, the jacking screws and the bearing housing surfaces.

This is not really an ideal arrangement when the assembly is to be subject to vibration which could easily loosen the fasteners that the assembly relied on.

It appeared that it was very likely that the increasing vibration levels of the failing pump could cause the locknuts to become loose and thus the axial location of the bearing housings would be compromised.

This possibly would explain how all of the failures were seizures of the axial face of the impeller despite the impeller being axially restrained on the shaft even when the bore was worn radially.

After a few weeks I was informed that a failed vacuum pump was being removed.

I arranged for it to be transported to a local well equipped maintenance workshop where detailed findings could be taken as the unit was stripped.

Upon stripping down it was firstly confirmed that the impeller was in fact seized in the regularly seen manner of recent failures.

Before removing any parts the locking nuts and jacking screws were tried. They were no longer locked in position. This seemed to confirm that the final failure mode was at least contributed to (if not caused) by the loss of axial location for the bearings.

Further notes were taken during the strip down, but the most noticeable fault was that the key way in the impeller had worn away over the key to such an extent that if the shaft keyway was at 12 O'clock the impeller keyway was now at 10 O'clock. The key and keyways had been markedly rubbed away to accommodate this.

Of course, the impeller was now eccentric to the shaft since as it had rubbed away the key it had ridden up and over the top of the key.

As the wear progressed the impeller would move steadily more eccentric. This exactly explained the gradual deterioration of the vibration experienced from the pumps when they were operating.

Under magnification of 10 times the failure mode of the key could clearly be seen.

Under a magnifying glass, longitudinal beach marks could clearly be seen across the remains of the key.

The markings got gradually wider in the direction of wear of the impeller. The failure mode was a fretting failure.

Experience shows that Titanium, when running on Titanium, is particularly susceptible to this type of failure mode unless careful precautions are built into the assembly.

Having completed the strip down, attention turned to the replacement parts being used.

A new shaft, impeller, keys etc were obtained from the maintenance stores.

When the parts were all checked out for tolerance it was noted that the impeller was a very loose fit on the shaft.

When asked about this, the plant maintenance supervisor told me that when they were overhauling the machines on a breakdown basis in their site workshop they had to strip and build them in the shortest possible time.

This meant that he had changed the specification of the impeller bore to shaft journal fit from an interference fit to a clearance fit.

The supervisor explained to me that the plant workshop didn't have the required press and special tools to deal with an interference fit and still turn the pumps round quickly. This of course was very true the local maintenance team were not equipped for this type of precision work at all.

It seemed logical to me that this explained how the fretting of the keys, shaft and impeller was initiating.

The looseness of the impeller on the shaft meant that the drive from the shaft was entirely through the keys.

It seemed that slight pulsation's during rotation of the impeller as the impeller vanes passed the ports in the pump could lead to the start of the fretting process on the side of the key and the impeller and the shaft keyways.

Once the fretting process has started it tends to accelerate as the wear debris builds up between the surfaces and acts as a kind of abrasive between the opposing surfaces.

The failure process appeared to be-

1 Looseness between the impeller and the shaft allowed fretting of the contacting surfaces of the impeller, shaft and keys to start.

2 Having started off, the fretting proceeded to cause the impeller to go eccentric to the shaft.

3 As the fretting proceeded, the impeller gradually went more and more eccentric.

4 In turn once the vibration became sever, it led to the locking screws vibrating loose and therefore, axial location being lost on the bearing housings.

5 This allowed the impeller to rub the inside of the end cover, welding the impeller to the end cover.

As a solution to the problem I proposed that we move to a heavy interference fit of the shaft into the impeller.

I also proposed that we could actually weld the impeller to the shaft making it a permanently built assembly.

I also suggested a system of positively locking the axial bearing location by setting up on the jacking screws, measuring the gap on the bearing housing assembly and machining spacers to exactly locate the housings. By setting the unit up this way internal clearances would be unaffected by vibration thus eliminating a consequence of vibration in the unit.

The plant maintenance team however, did not like the idea of a shaft and impeller assembly that couldn't be disassembled.

Despite my assurances that it wouldn't have to be disassembled again, the welding option was rejected.

However, the spare shaft had its journals spiral welded up and re-machined to give a heavy interference in the impeller bore.

The manufacturing drawings for the spare shafts was updated to the new sizes.

An assembly procedure was written with the following main points

1. Immerse the shaft in liquid nitrogen whilst suspended vertically from a crane.

2. When the shaft was fully cooled it was to be dropped into the bore of the impeller.

3. The assembly was to be balanced before final build up.

4. The pump when assembled would be set up using the jacking screws to centralise the impeller end clearances, the housings then locked into position using machined spacers on the jacking screws.

This method of build up was carried out on the first pump to be overhauled and the pump ran with extremely low levels of vibration for 3 years that the author knows of.

This was then adopted as the standard overhaul procedure.

Conclusion-

Due to circumstances beyond their control, the facility had been forced into changing a long standing working arrangement that had been quite satisfactory for them.

Unfortunately for them, by deciding to overhaul the machines in the local plant workshop they didn't have the equipment to handle repairs to the required standard.

Instead of looking for a workshop locally that could provide a satisfactory service to them they decided to make alterations to the limits and fits to facilitate local repair.

Further, they became more concerned about how quickly they could turn round repair of the units rather than finding out what was the root cause of the failures.

The cause and effect of changing the fit of the impeller on the shaft causing the unreliability was completely lost to them.

Only when a fresh pair of eyes came along and scrutinised what they were doing did they realise the mistake they had made.

In fact, the company policies regarding authorising engineering changes may have caused them to look a little deeper into what they were doing when they made this change. However, in this case the change wasn't considered by the plant engineer to be worthy of raising the paperwork and registering the change. This was a mistake.

Looking at it from this point of view, it is extremely fortunate that the only effect of making this change was one affecting reliability and costs.

It could have just as easily created safety problems in which case the unauthorised nature of the change would have been much more serious, maybe even releasing hazardous chemicals to the environment.

Follow up-

The vacuum pumps were both built to the revised overhaul procedure and the spare parts inventory was changed to the new drawing revision.

After overhaul the pumps ran for three years without problems of any kind whatsoever.

The pumps are still operating and will continue to do so until the plant reaches the end of its life.

The savings in maintenance spend and increased reliability have played an important part in returning the plant's business to profitability.

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About the author-

Stephen H Shakeshaft is a Mechanical Engineer based in the United Kingdom. He is the Principal Consultant and Director of Stephen H Shakeshaft Consulting Ltd., an engineering consultancy specialising in optimisation of existing assets and engineering design of new build projects.

Stephen has over 30 years experience of working at the "sharp end" as well as the "back room" of manufacturing industries with clients in the chemical, utility, metals, industrial gases and pharmaceutical businesses.

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