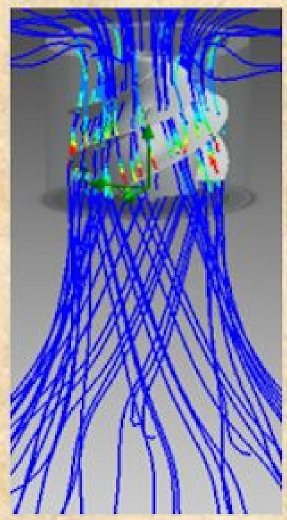
Failure Analysis of Jet Boat's Wear Ring and Impeller.



Vapor can damage more than you think...

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Properties of Materials (ME 3034) December 2nd 2016

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Summary, Conclusions and Recommendation

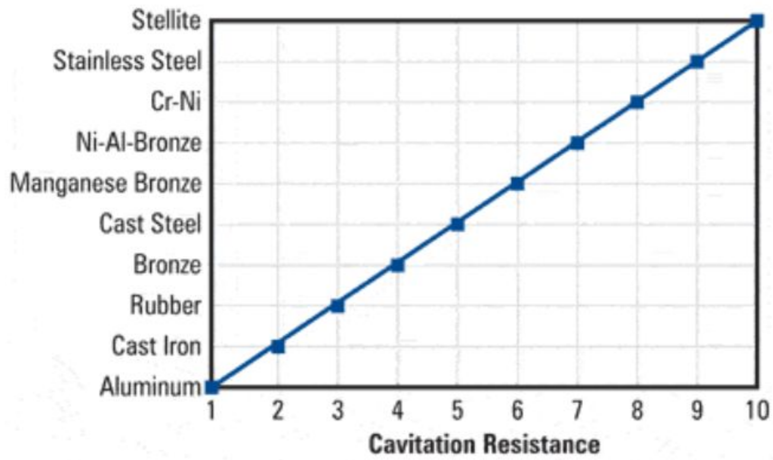
About the Part

The part that failed was from Mercury Marine Sports Jet 2010 model, figure 2. We analyzed 2 similarly damaged components, the wear ring and the impeller; Figure 1, and 3 respectively.

Summary Figure 1,2,3 (left to right)

Materials Used

The impeller is made of a stainless-steel alloy that the manufactures call X7 and the wear ring is made from an aluminum alloy called XK360. Our main theory for failure is cavitation and this graph below indicates that while the aluminum wear ring is designed to take less cavitation damage then the stainless steel impeller.



Summary Graph 1

Overview of What Caused the Failure

The reason these parts failed is due to cavitation. In the case of the aluminum wear ring there is also a significant decrease in hardness, indicating that the heat from the engine and exhaust port could be reducing the hardness of the aluminum. Therefore, the wear ring cavitated only at the top due to the combination of vapor that causes cavitation, and the decreased hardness at the top of the wear ring. Additionally, the impeller also cavitated, but this was due because the engine was run at too high RPM for too long.

Recommendation Summary

There are a couple recommendations that would likely fix this failure. One is to add a plastic liner that fits along the outside of the wear ring. Also, using JB weld to fill in the cavitated areas can help restore performance. One last way to improve this would be to change the material of the impeller to something more resistant to cavitation, such as a higher grade stainless steel. There may not be a need to redesign the part if the reason for failure was due to unusually extreme temperature from the engine, or running it at too high RPM. In which case checking the engine for maintenance troubles would be advised, and limiting the max RPM to a lower value, to avoid abuse and overuse.

<u>Introduction and Background Information</u>

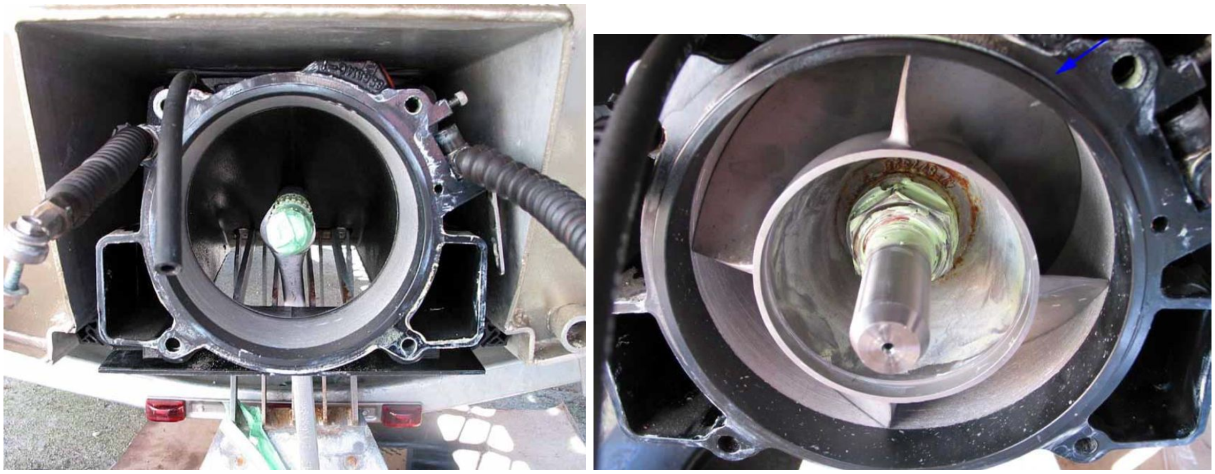
This failure analysis of a sports jet impeller and wear ring is being done for Dr. Henshaw. A previous student of Dr. Henshaw donated the parts from his friends' jet boat. Due to part of the aluminum wear ring being overheated by the exhaust port, cavitation occurred in the area which led to failure of the part. Suicide Squad analyzed these parts to determine exactly how they failed.

Both the impeller and wear ring were designed and manufactured by Mercury Sports. The wear ring is made of XK360 which is an aluminum alloy. The impeller is made from X7 which is a stainless-steel alloy. We do not know exactly what is in the alloys because Mercury does not make that general knowledge.

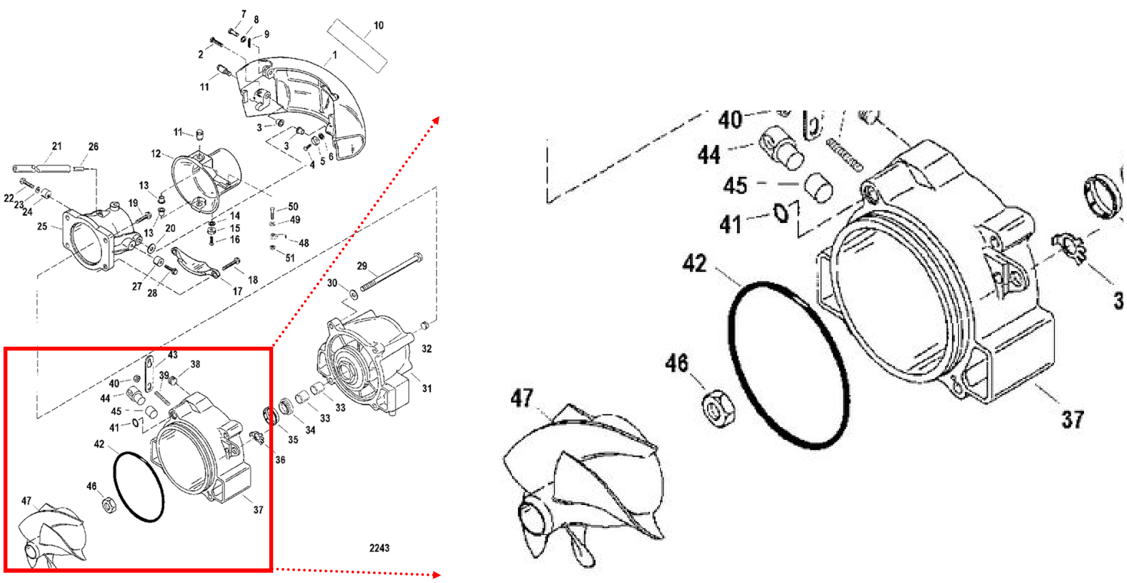
<u>How It's Assembled</u>

The entire pump assembly is designed to be easily constructed and deconstructed to perform regular maintenance on the impeller setup and path of flow due to the high variability operating environment of this machine — including the possibility of solid masses breaching the intake grate or becoming lodged in it, damage from both normal and abnormal levels of cavitation, and lubricant degradation affecting the drive shaft of the impeller. Without going into details on the assembly of the boat and motor, the onboard motor is mounted in the stern section of the hull, and the hull is cut to allow the flow to enter its path. The Stator and wear ring are casted aluminum parts that are bolted together and serve as the structural base of the jet drive assembly, which itself is the base of the engine above it. After the inlet, the drive shaft protrudes through the flow region to connect with the impeller, which sits in the Wear Ring. From the wear ring backwards, the Stator, Flow Nozzle and reversing gate are bolted together in sequence, so that the entire drive may be easily disassembled. To further aid in reassembly, all bolts and screws are reusable and can be adjusted using a standard imperial socket set, except for a custom Mercury tool *(serial no. #91-850297)* used to attach the impeller to the drive shaft.

Introduction Figure 1: Parts that must be removed to Access the Impeller and Wear Ring. From Left to Right: Steering Cable, Mounting Bolts/Plate, Flow Nozzle (Rudder), Reversing Gate/Spring, Stator, and the impeller itself, which must be removed to expose the inner surface of the wear ring.



Flow through intake grate and wear ring, showing drive shaft with impeller removed and Comparison with mounted impeller in wear ring
Introduction Figure 2,3 (left to right)



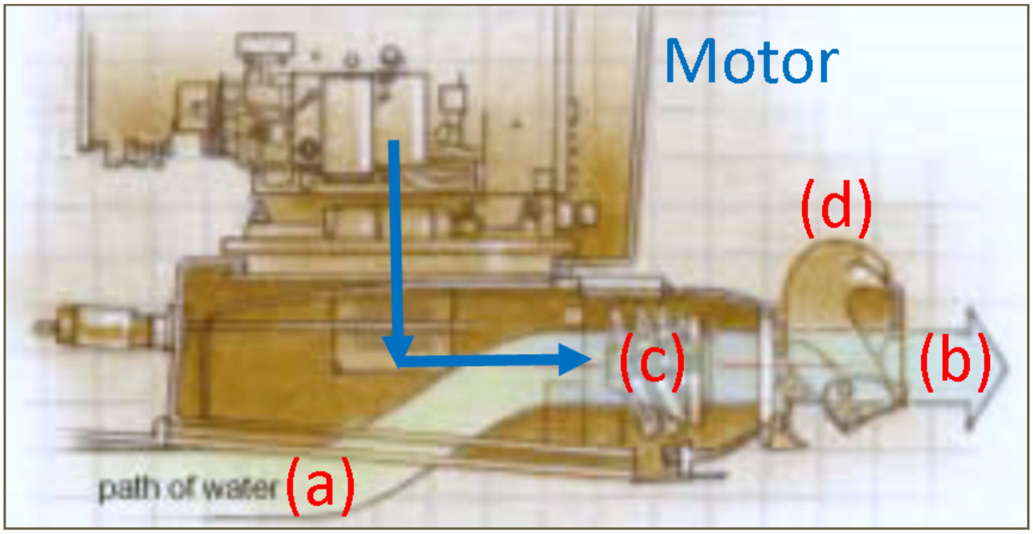
Introduction Figure 4: Schematic of Nozzle and Rudder Components of M2 DFI 200 Jet Drive

<u>How It Works: Onboard Marine Motor</u>

The Jet Pump is an axial pump, driven by the impeller which itself is driven by a gas-powered engine. In our case, this engine maxes out at 200 HP, which correlates to an RPM of 5650. There is no transmission assembly, thus the RPM of the engine equals the RPM of the impeller, as used later in the CFD calculations.

As an axial pump, the impeller is mounted normal to the flow of the liquid around it, as shown in Figure 4. The pitch of the blades is almost linear, with a slight bend near the middle of the impeller to decrease the pitch. The pitch curve dictates how much force the impeller imparts to the flow, and also affects the drop in vapor pressure that can lead to cavitation. Furthermore, it can be observed that this is a ‘high suction energy pump” because the radius of the “eye” — the radius of the outside surface of the impeller cylinder — increases to nearly 400% its original radius by the tail end of the impeller. The purpose of this is to accelerate the fluid into the most thrust-imparting region of the impeller blades, and dually to reduce the cross-sectional area of the fluid flow. These effects on the fluid flow are explored in more detail in the CFD analysis. A converging flow nozzle that is attached to the steering column via cables serves as a rudder, and as the flow outlet from the pump into the ambient atmosphere or fluid.

If the thrust needs to be reversed, a “Reversing Gate” is able to swing down and redirect the output by an angle of approximately 150°. This is not very efficient, as a majority of the force must be absorbed by the internal impact surface of the reversing gate opposite the original direction of normal thrust, however high thrust is not required for reverse drive. The fluid is at very high velocity, thus the reversing gate is designed with contours that allow for maximal redirection of thrust without causing damage. The pressures involved are still significantly lower than those at the impeller region, due to the widening of the fluid cross-section. The impeller, reversing gate, and flow outlet and inlet are shown and labeled in Intro Figure 1.



Intro Figure 5: Labeled as follows in red: (a) is the inlet of flow, (b) is the outlet of the flow, (c) is the impeller, and (d) is the reversing gate. The drive shaft from the motor is shown in blue.

Visual Examination

Impeller Failure Location

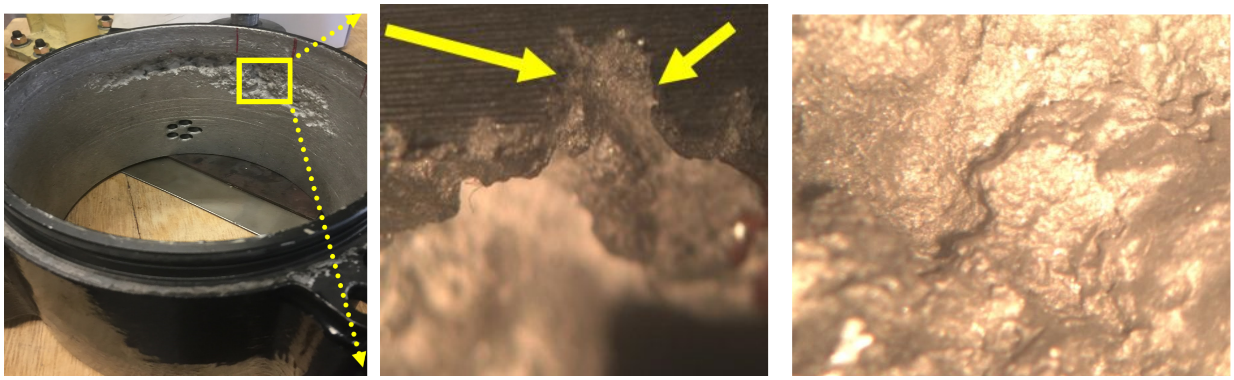
Visual Examination Figure 1,2

Once receiving the wear ring and impeller there were several noticeable problems. On the blades of the impeller there was an even distribution of cavitation (Figure 1,2). There was at least some cavitation on each separate blade in the same spot. With the wear ring, there was a large area of cavitation that was centered around the exhaust port (Figure 3,4). There was more cavitation to the right of the exhaust port than the left, following how a fluid would flow through the ring. On the bottom of the ring there was very slight cavitation. Using the casting number of both parts, we were able to determine that they came from a 2010 Mercury Marine Sports Jet.

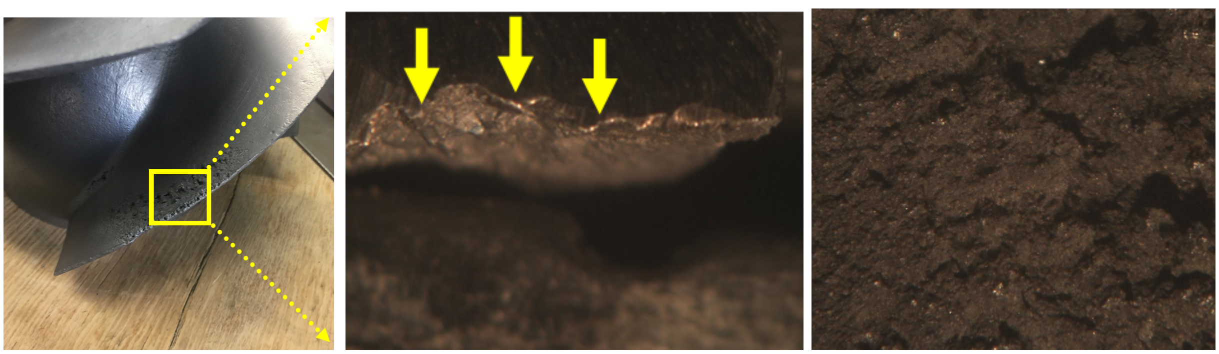
Visual Examination Figure 3,4

<u>Microstructural Examination</u>

To determine the material properties of the wear ring and impeller, an optical microscope was used to examine samples of the damaged surface and of the microstructures of each material. The damaged surface of the inner wear ring chosen for the sample is selected by visually averaging the damage and choosing the most average region, as highlighted below.

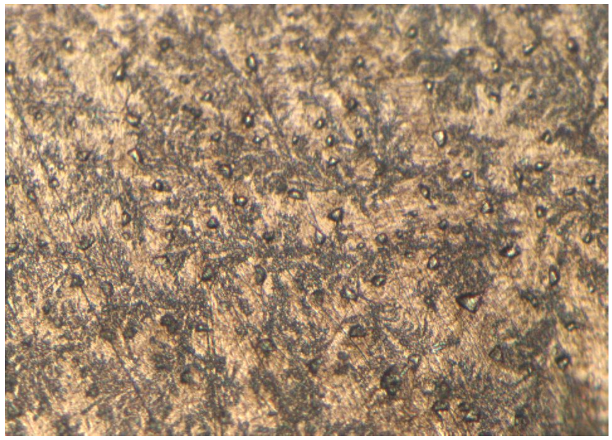


Low magnification (at middle: 20X, at right: 50X) microscope pictures of surface damage on Aluminum Wear ring. Cavitational Damage Profiles on surface edge are highlighted with arrows.
Microstructural Examination Figure 1,2,3 (left to right)



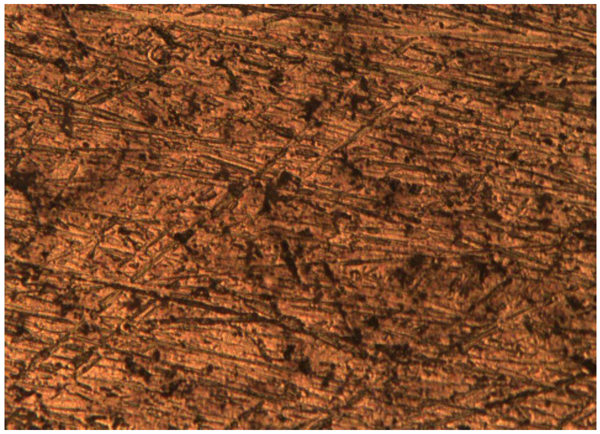
Low magnification (at middle: 20X, at right: 50X) microscope pictures of surface damage on Stainless Steel Impeller. Cavitational Damage Profiles on surface edge are highlighted with arrows.
Microstructural Examination Figure 4,5,6 (left to right)

To further examine the metallurgical structures present in our samples, a test to highlight their grain structures on the microscopic level was performed. The portions of each sample indicated by the zoomed photographic regions above were cut out and mounted in a protective layer of epoxy. The purpose of this is to stabilize the sample for polishing and etching of one exposed face. The surface was observed before and after polishing, and the microstructural photos below were edited visually to maximize contrast and detail.



Low magnification (50X) microscope Pictures of Grain Structure of Stainless Steel Impeller
Microstructural Examination Figure 7

According to the manufacturer, Mercury Marine, the X7 stainless steel alloy is "30% stronger and 4x more durable than conventional stainless steel". The details of the materials that go into the X7 alloy and the heat treatment it receives are not published or otherwise available. The large particulate dots in the grain structure may be the result of a precipitation hardening treatment. This is highly likely, considering that it would advantageously harden the impeller without reducing durability if treated properly, and also stainless steels may contain many different secondary elements that could precipitate out: manganese, chromium, nickel, molybdenum, nitrogen, copper, titanium, phosphorus, sulphur, selenium, niobium, silicon, cobalt and calcium. Based on the appearance, the precipitate could likely be chromium. The ultimate tensile strength of the X7 Stainless Steel Alloy is found to be approximately 112 ksi from our hardness testing data and microstructural photographs.

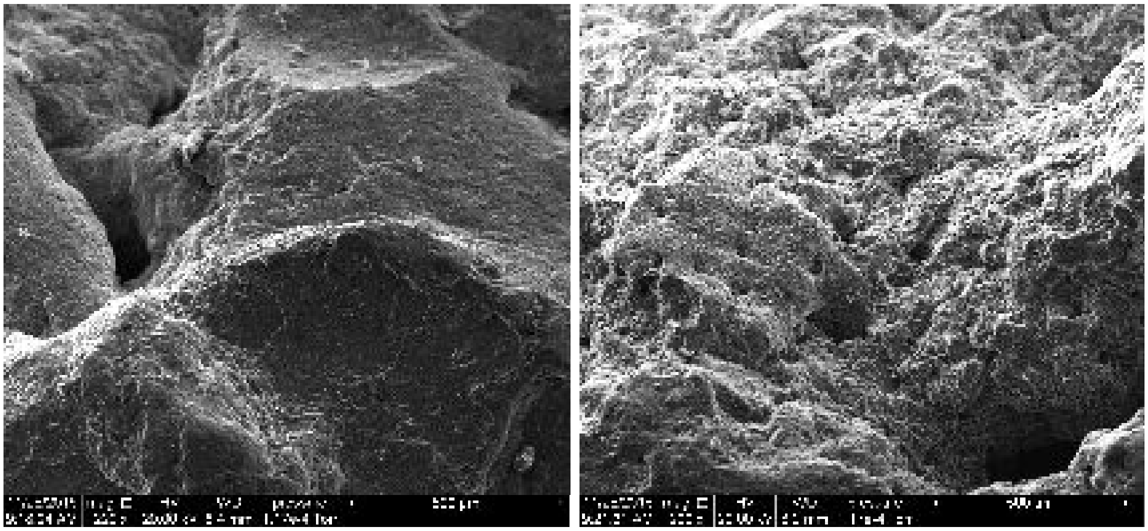


Low magnification (50X) microscope Pictures of Grain Structure of Aluminum Wear Ring
Microstructural Examination Figure 8

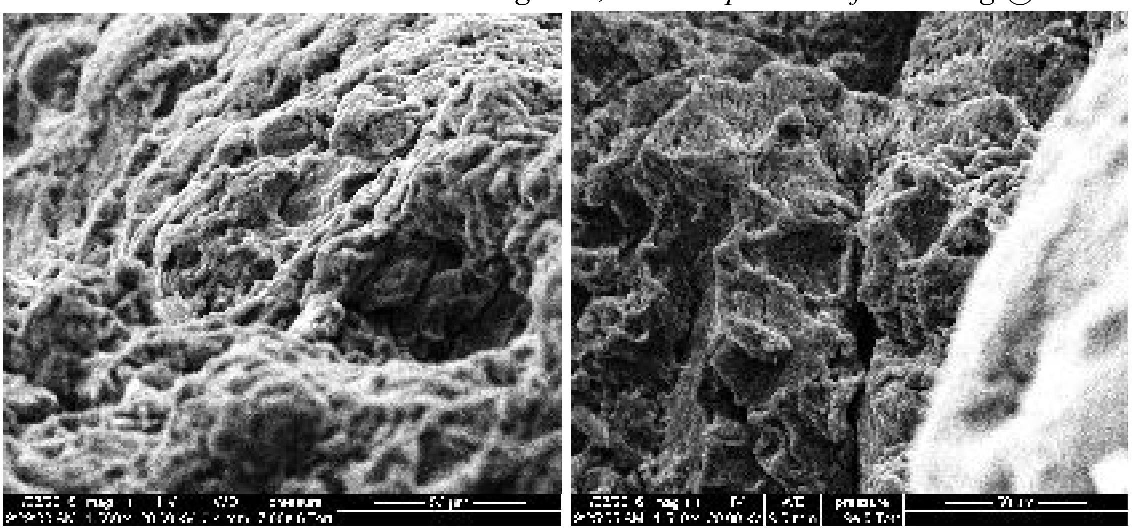
The grain structure can be seen in both microscope photos, although significant scouring is seen in the aluminum microstructural photo. The ultimate tensile strength of the XK360 Aluminum Alloy is found to be approximately 49.3 ksi from our hardness testing data and microstructural photographs, Figures 7 and 8 and Table 1.

<u>SEM</u>

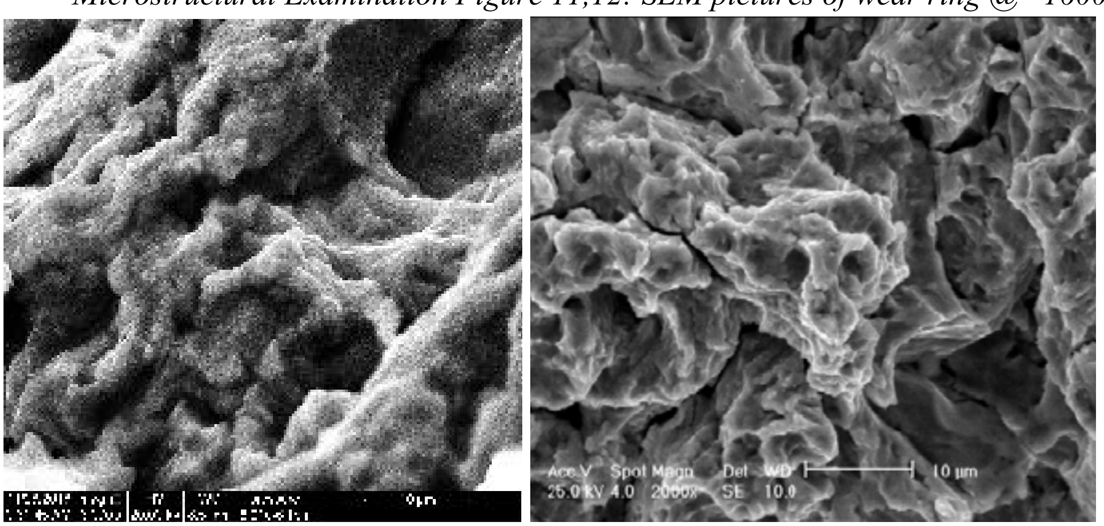
Scanning Electron Microscopy was also used, to better understand what was happening during the damaging event, and to rule out various other theories about the source of the damage such as corrosive or particulate-impact damage. Grain structure boundaries appear to be visible in some of the photos, seen especially in the second photo of Figure 9. The “sponge-like” surface is a well-known indicator of cavitational damage; additionally, the size and orientation of the ridges appear to be the direct result of a cold-working process. Should these ridges show any form of cratering or directionality, particulate impact damage could be a cause, however this is not seen in our photographs.



Microstructural Examination Figure 9,10: SEM pictures of wear ring @ ~220x



Microstructural Examination Figure 11,12: SEM pictures of wear ring @ ~1600x



Microstructural Examination Figure 13,14: SEM @ ~6000x (Left) vs Reference (Right)

Hardness Test Results

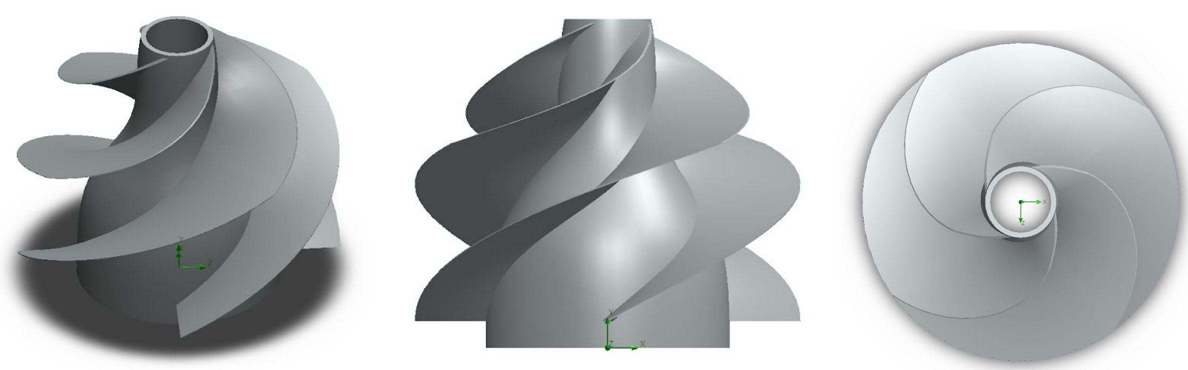
hardness piece	place 1	place 2	place 3	average±COV	type of scale
steel on impeller	55.50	61.90	61.90	59.77±6%	rockwell A
on top of wear ring	49.70	41.30	55.70	48.9±15%	rockwell F
on far edge	82.20	72.50	86.30	80.33±8%	rockwell F

Hardness Test Results Table 1

Hardness data of three spots for every specimens are collected at place1 place2 and place3. Both the steel on the impeller and the aluminum on the far edge of the wear ring have coefficients of variation less than 10%, material on top of the wear ring has 15% COV. The hardness of the aluminum on the exhaust port cannot be measured since it is too soft to test (even with microhardness test). From data, the area closer to cavitation is less hard than further away. Aluminum on exhaust port has 43.3% less hardness than the same material from far edge although they are made of same material.

Computational Fluid Dynamics (CFD analysis)

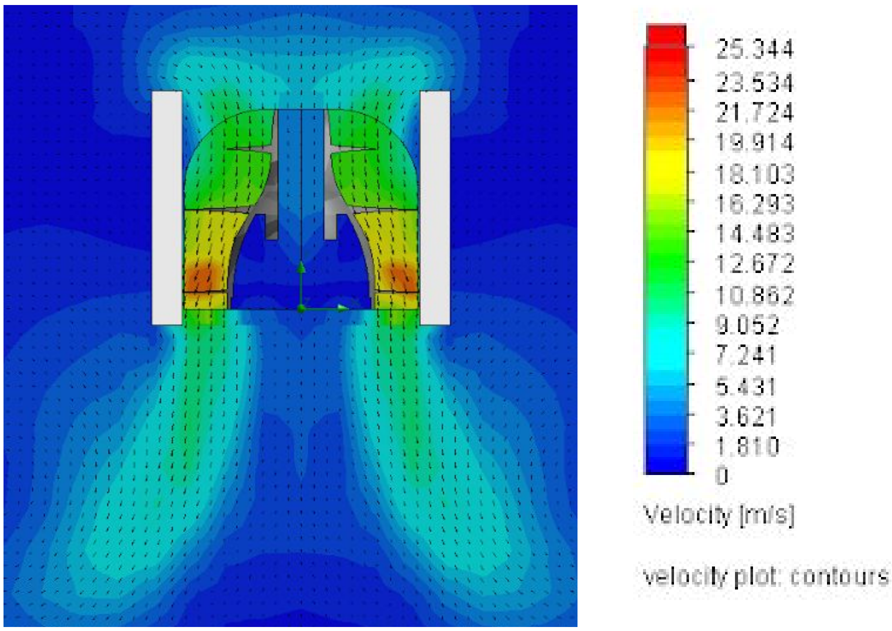
To better analyze what is happening with the fluid inside the wear ring, a Computational Fluid Dynamics (CFD) analysis was run to understand the velocity, pressure, and vapourization inside the part. We modeled the impeller in *solidworks*, figures 1,2,3, and the wear ring as a basic circular tube. We then ran an analysis using the fluid simulation in solidworks. For this simulation the fluid was modeled as freshwater, and the impeller was running at 500rad/s (4775 RPM). The max RPM of the engine is listed as (5160-5650) RPM. It is important to note that when solidworks models a rotating part, the part is actually stationary relative to other parts. And the fluid moves. For this case, the impeller and wear ring are relatively stationary, with a fluid boundary rotating around the impeller. This is evident in the side view pictures such as figure 4 where the top of the impeller has a noticeable dome , which is the fluid rotation boundary. Additionally, in the last figures (CFD figure 11,12), the wear ring and impeller are stationary relative to one another, which means the analysis will be modeled as if looked at a single point in time.



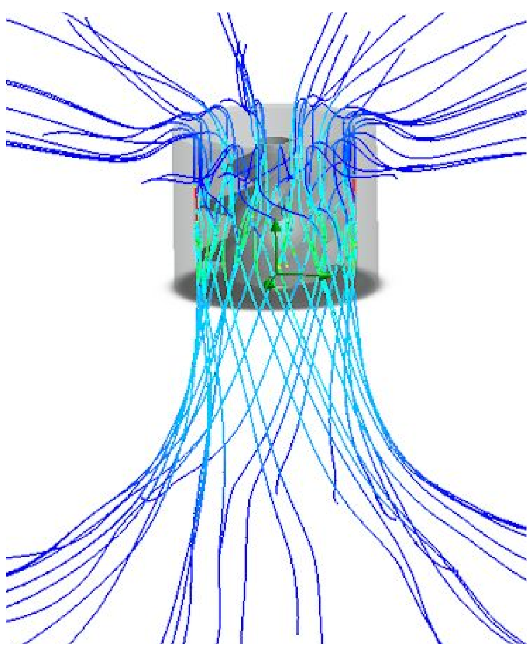
Impeller modeled in solidworks (CFD figures 1,2,3)

Velocity Plot

The Contour plot, figure 4, and trajectory plot, figure 5 models the flow of fluid through the wear ring and the velocity associated with this flow. At the speed modeled (500rad/s) you can see the max velocity is ~25m/s localized right at the bottom of the impeller.



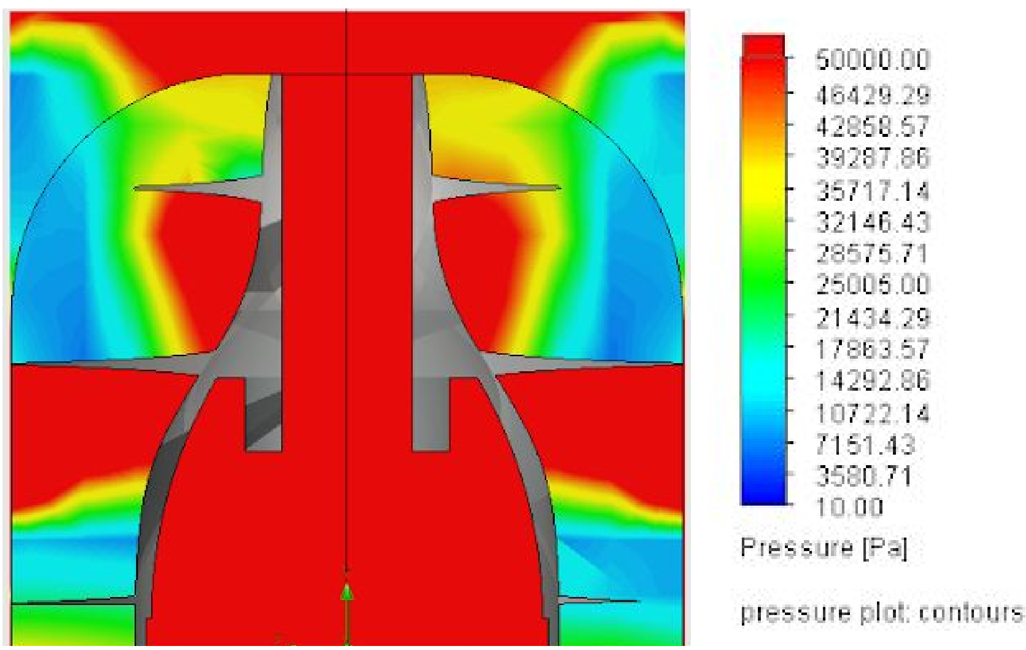
Velocity contours: (CFD Figure 4)



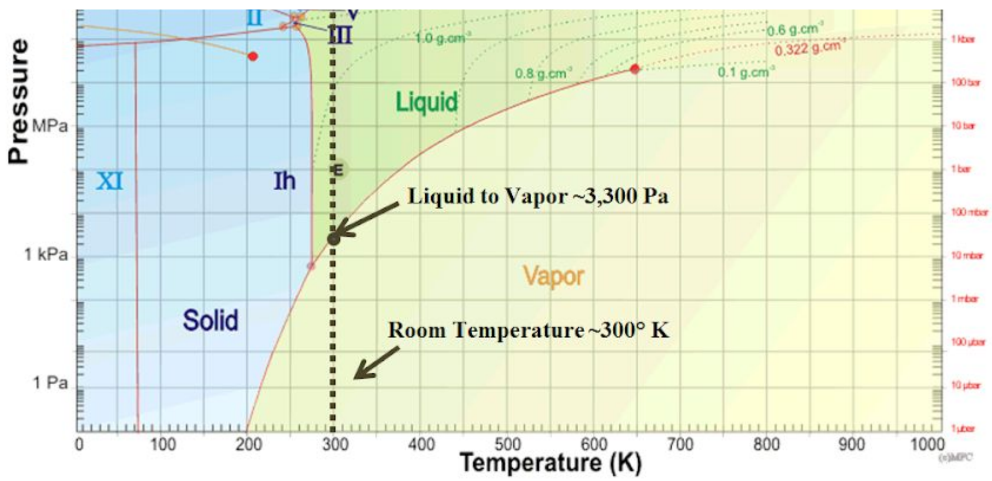
Velocity trajectory plot. (CFD Figure 5)

Pressure Plot

The pressure plot below, figure 6, models the pressure of the fluid as it flows through the wear ring. At room temperature fluid normally vaporizes at less than 3,300Pa. On this diagram you can clearly see areas as low as ~7,000Pa or less right near the blades. While this does not definitively show vaporization, it is so close to the vaporization point compared to normal 101.3kPa pressure, that there is at least partial vaporization. Additionally the temperature from the engine means that the fluid will likely start to vaporize at higher pressures as seen in the phase diagram, figure 7.



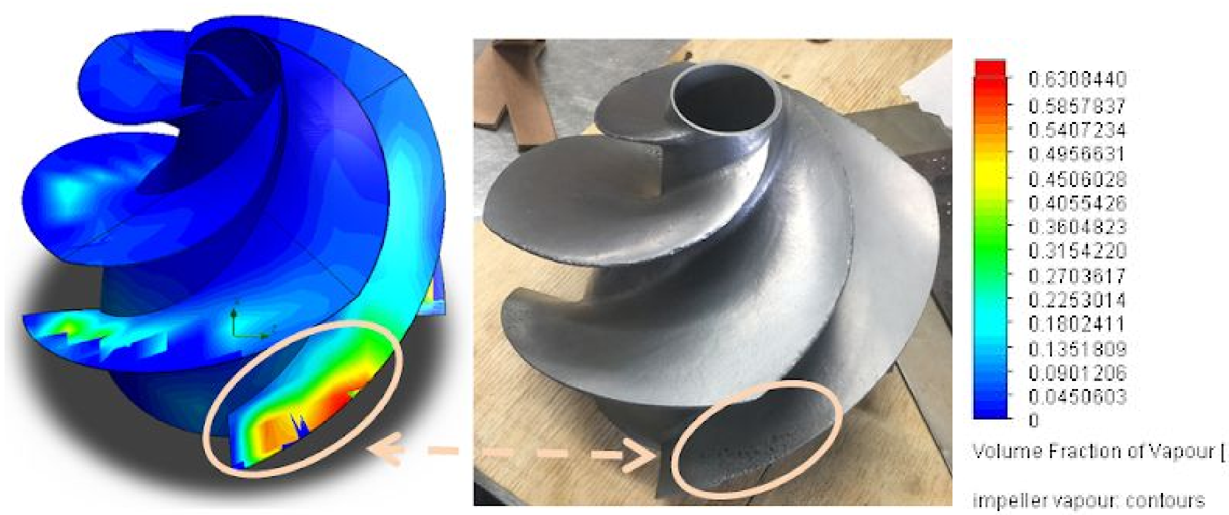
Pressure Plot (CFD Figure 6)



Phase Diagram of water (CFD Figure 7)

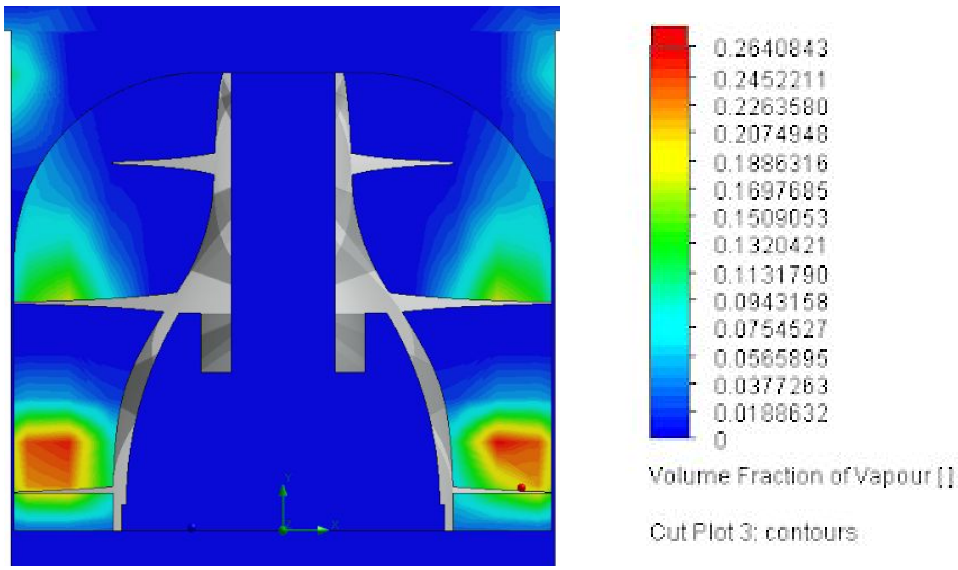
<u>Fluid Vaporization Plot on impeller</u>

Figure 8 and Figure 9 both model the percent of vapor on the impeller. Figure 8 indicates there is at the highest point ~60% vapor. This show that there are a lot of bubbles that are forming and subsequently crash into the metal of the impeller causing damage when they turn back into liquid. This is indicative of cavitation. It also has the highest percent vaporization in the same region on the real part, showing that this is a good model to predict the damage.



3D fluid vaporization plot (CFD Figure 8)

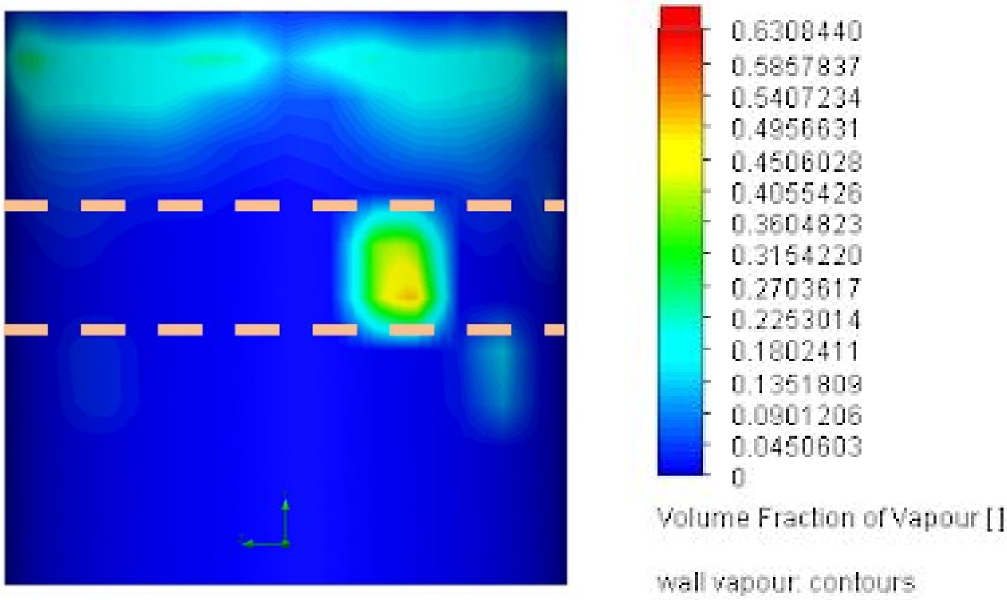
Comparison picture (CFD Figure 9)



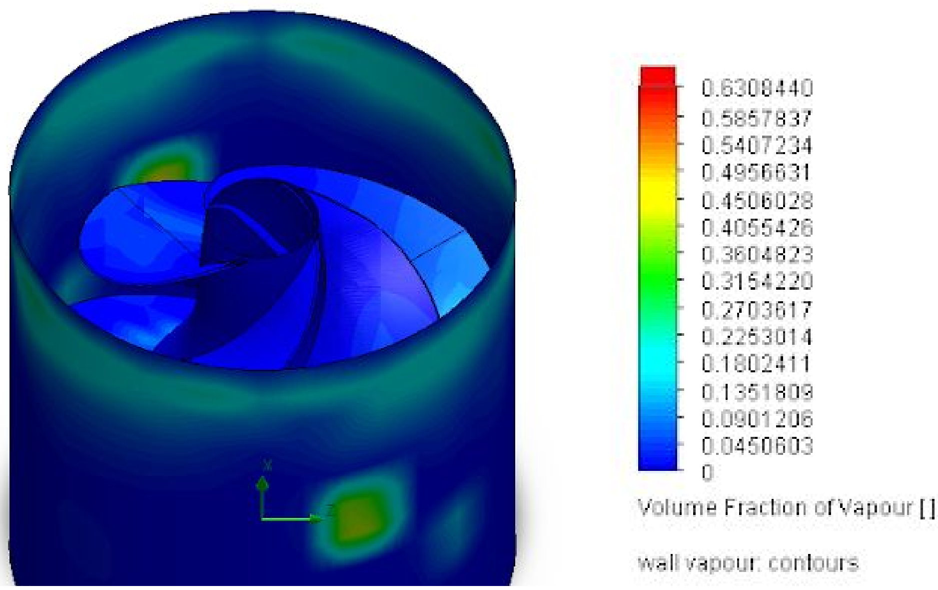
fluid vaporization plot cross section (CFD Figure 10)

<u>Fluid Vaporization Plot on Wear Ring</u>

Figure 11 and 12 picture the plot of percent fluid vapor on the wear ring. The dotted lines in figure 11 represent where the plot should actually be. It should look like that one localized region all between the dotted lines. This is because solidworks cannot model rotating bodies, only rotating fluid. Effectively that means the relative to the wear ring, the impeller is not moving, but the fluid is rotating around the impeller giving it the same effect, but interfaces like these won't be modeled perfectly. The localized region in figure 11 is actually where the blade is closest to the edge, which you can see in the 3D model in figure 12. The percent vaporization of this wear ring is at max about 40% and the dotted lines also represent where the failure is on the real part. further helping to confirm the theory of cavitation.

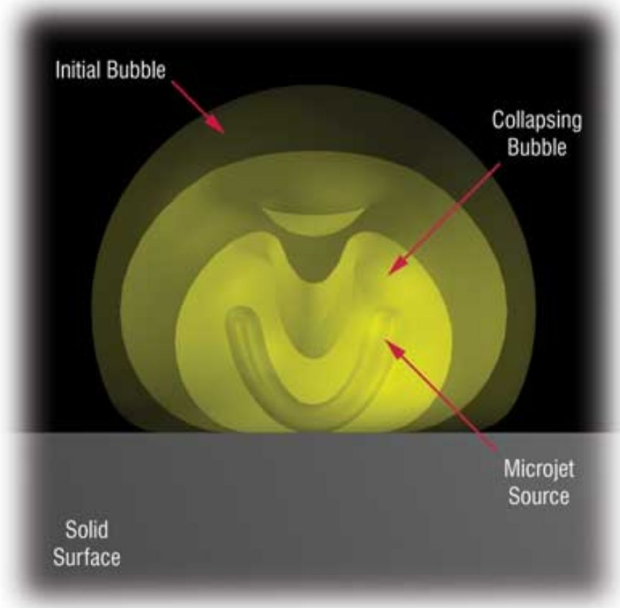


Wear ring inside damage (CFD, Figure 11)



3D Wear ring inside damage (CFD Figure 12)

Discussion



Discussion Figure 1: Microjet formation at surface of cavitational damage

What is Cavitation

When the pressure of the surface that fluid and solid attached surface lower than fluid's vapor pressure, it will create bubbles on the surface. Also the gas dissolved in liquid can create bubbles like soda, when the bubbles come to the place where liquid's pressure greater than the pressure of the bubbles, the bubble will collapse and release force and heat. After the force and heat work on solid surface various of times, material will peel off and puddles will occur, that is cavitation. From observation, the surface near the exhaust port on wearing looks like sponge, and the sponge-looking surface tend to move to the direction of impeller orientates. The observation fits the character of cavitation (sponge-looking surface, not everywhere). The bubbles that caused cavitation came from the exhaust port, since the exhaust port is the outlet of engine's cooling system. The heat of the exhaust did not directly cause cavitation, but allowed its damage to grow more quickly due to the softness of the heated aluminum.

CFD Model to Accurately Predict Damage

The percent fluid vapor plots in the CFD analysis correlate almost perfectly with the damage observed. Most notably the wear ring percent fluid vapor plot, CFD figure 11, models vapor exactly where the wear ring took the most damage. These computations serve to link vaporization of the water with the damage. Vaporization bubbles are the primary causes for cavitation, which means that this CFD analysis models the damage most likely as cavitation on the exact areas it was damaged. Furthermore, The comparison between the 3D impeller vapor plot, CFD figure 8, and the real part picture, CFD figure 9, also shows that the where the most percent vapor is located, is where it was damaged on the real part. Further supporting the theory of cavitation.

Microscope pictures correlate with cavitation

The microscope photographs show a type of visual damage that is commonly associated with cavitational damage for both types of metal. The X7 Stainless steel shows what appears to be bands of martensite that appear to be organized into leafy, ‘branch-like’ structures throughout the steel. The larger spheroidal structures appear to be the result of particulate hardening. The aluminum does not show any large deposits of any alloy element, which is to be expected as the manufacturer claims it has significantly lower carbon content than similar aluminum alloys.

The Scanning Electron Microscope photos showed direct evidence of cavitation when compared to reference images of similar metals. This experiment also served to rule out the possibility of chemical damage, as no evidence of corrosive or particulate-impact damage.

Exhaust port and engine heat theory

Using far edge hardness data as reference, the material closer to the exhaust port is not as hard. Because the aluminum alloy became heated, temperature cycling occurred which reduced the hardness of the material. This process is considered annealing. Also, there may have been some chemical reaction that took place during the process, further analysis is needed.

The failure of these parts occurred because the exhaust port was overheated. When the hot fluid from the engine came through the port and into the wear ring, the metal lost its original hardness level. We know this because of our hardness testing. It shows that the metal is more weak near the exhaust port compared to metal that is on the other side of the ring. Because of this, cavitation occurred in a large amount right over the exhaust port. Once the fluid was out of the port and in the ring, it flowed to the right and made that part of the ring lose its hardness as well. The cavitation got deep enough to the point where it broke through the wall and into the exhaust port creating a hole. The cavitation that occurred on the impeller is normal cavitation that would occur over time from use.

Discussion Figure 2: wear ring

Overuse and Abuse of engine theory

It may be possible to avoid this failure without changing anything to the parts in question, if the failure is due to an additional, external failure that was part of the larger system: as the heated engine exhaust is to blame for the wear ring failure and increased cavitational damage zone, and the wear ring shows no other signs of casting or material flaws, and the fact that the casting is proven to follow a normal cavitational wear pattern which is not a failure, the engine itself may have produced anomalously high exhaust temperatures that caused softening of the metal in this specific case. Thus, the design flaw may rather be a result of an engine design flaw, or simply a case of poor engine maintenance or operation leading to abnormal exhaust output functions. Hence further testing of the part in question with the engine used previously would be necessary to determine the source of the failure, which was not possible due to the remaining question of our part's origin (the original 'owner' had no details as the parts were from a friend who could not be identified or contacted).

Conclusions

1. Cavitation is the most likely cause since the CFD analysis showed fluid vaporization, and the SEM pictures correlated with known cavitation examples
2. The heat from the engine and the exhaust port is what caused only the top of the wear ring closest to the impeller and the exhaust port to cavitate.
3. Battery acid is not likely the cause due to no distinguishable stains, and the damage being on the top, where leakages would not normally settle.
4. The engine could be overheating or not functioning properly, since the hardness data shows lowered strength near the top of the impeller.
5. The max RPM combined with possible other factors, is able to cause cavitation which means that the max operable RPM is too high for this model.
6. Debris running through the impeller wear ring likely did not cause the damage,due to both the CFD analysis showing fluid vapour at the damaged parts indicating cavitation, and examinations both full sized and microscopic indicative to cavitation damage.

Recommendations

1) Use JB weld to fill in cavitated areas to restore factory performance.

2) Switch the material of the impeller to something more resistant to cavitation, such as a higher grade stainless steel, to improve the lifetime of the part. The

3) Use a removable plastic wear ring liner that can be replaced for $14.99.

4) Check the engine for overheating and run maintenance if necessary.

5) Limit max revolutions per minute to avoid overusage.

Appendices

References

Jason Fishell: Experienced Program Director within the construction industry, specializing in contract and commercial management of large industrial capital projects. Graduate of Mechanical Engineering from the University of Maryland, College Park. Currently acting as a consultant with previous employers including Bechtel, Areva, Day & Zimmermann, and Mitsubishi Nuclear Energy Systems. Previous projects include construction and maintenance within various domestic nuclear power facilities, construction of pharmaceutical related facilities for Eli Lilly, construction of the new Walter Reed Military Hospital, and mission critical work within data centers.

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