Cavitation erosion resistance assessment and comparison of three francis turbine runner materials

CAVITATION EROSION RESISTANCE ASSESSMENT AND COMPARISON OF THREE FRANCIS TURBINE RUNNER MATERIALS

Markku Ylönen[1,2,3,*], Pentti Saarenrinne[1], Juha Miettinen[1], Jean-Pierre Franc[2], Marc Fivel[3], Tuomo Nyyssönen[1]
[1]Tampere University of Technology, 33720 Tampere, Finland
[2]Université Grenoble Alpes, CNRS, Grenoble INP, LEGI, 38000 Grenoble, France
[3]Université Grenoble Alpes, CNRS, Grenoble INP, SIMAP, 38000 Grenoble, France
[*]Corresponding author: markku.ylonen@tut.fi

Abstract

Cavitation erosion is the most important erosion mechanism in Francis turbine runner blades. For this reason, knowledge of a material's ability to resist cavitation is important in defining how suitable it is for use in a Francis turbine. In this study, three Francis turbine materials were subjected to cavitation erosion in a high-speed cavitation tunnel. One of the materials was a low-alloy steel and the other two were stainless steels. The cavitation tunnel produced an annular cavitation field on one face of a cylindrical sample. The test samples underwent cavitation erosion until the erosion had reached a maximum penetration depth of about 0.5 mm. The material surface profiles were measured at regular intervals to calculate volume and mass loss. These losses were compared to those of several other materials that had undergone the same tests with the same setup and operational parameters. The materials were compared according to their steady-state erosion rates. The steady-state erosion rate represents a material's ability to resist cavitation erosion once cavitation damage has already started to develop. The low-alloy steel eroded four times faster than the two stainless steels. One of the stainless steels tested here (stainless steel 1) had the lowest erosion rate, along with another previously tested stainless steel. The other stainless steel (stainless steel 2) had a slightly greater erosion rate than the first, falling into the same class as other lower grade stainless steels and a nickel aluminum bronze alloy. The results show that in choosing a turbine blade material, stainless steels outperform non-stainless ones. The choice of which type of stainless steel to use is significant in turbines with cavitation problems. The eroded surfaces were analyzed with SEM in order to study the erosion mechanisms, and these studies showed that most of the damage is probably due to low-cycle fatigue.

Keywords: Cavitation, Hydro turbine wear, Cavitation erosion resistance

Nomenclature
SEM = Scanning Electron Microscope

1. Introduction

The use of renewable energy sources, such as wind or solar power, is increasingly common in electricity production, which means that a large amount of power with modifiable output is required. The current solution is to make more use of hydropower to regulate the power grid, as this can respond to the rapidly changing demands for power. However, when the hydropower turbines have to operate

outside their optimum operational values, they experience cavitation and other disturbances. Cavitation erosion is one of the most significant mechanisms for wear in hydro machines. Therefore, information about the turbine material's ability to resist cavitation erosion is vital in both avoiding damage and/or estimating its extent after it has occurred.

Cavitation occurs in a hydro machine when the local static pressure of a flow falls below a certain limit, typically close to liquid vapor pressure. At this point, the liquid evaporates, forming small vapor bubbles that go with the flow. As the static pressure recovers, these bubbles collapse violently. Cavitation erosion occurs when a cavitation bubble collapses near a boundary, such as a turbine blade. The presence of the boundary causes the cavitation bubble to collapse non-symmetrically, which leads to the formation of a micro-jet of water that pierces the bubble and a shock wave due to the collapsing bubble walls [1]. When this micro-jet of water combined with the collapsing bubble ring hits the boundary, the stress on the material exceeds its yield stress, resulting in microscopic damage. This microscopic damage accumulates on the material's surface, eventually leading to fatigue and rupture on a macroscopic scale.

The main parts of a Francis turbine that suffer from cavitation erosion, along with their cavitation types, are: 1) the blade suction-side walls, inlet edge cavitation; 2) the runner blade trailing edges, travelling bubble cavitation; 3) the runner hub walls, inter-blade cavitating vortices; and, 4) the runner blades, leading edge cavitation [2-4]. An example of cavitation damage in Francis turbine runner blades, concentrated on the blade's trailing edges, is presented in Fig. 1. Cavitation may also occur in the draft tube vortex rope of a Francis turbine, but there the cavitation bubbles rarely collapse near any boundary structures.

The development of cavitation erosion in metals has three to four stages: incubation, acceleration, steady-state, and deceleration [5-9]. In the incubation period, an initially virgin material surface experiences plastic deformation, but there is negligible overlap of the cavitation pits. The material's ability to resist the onset of cavitation erosion is closely linked to the length of the incubation period. After the incubation period, the material erosion rate shifts to the acceleration period, when the initial pits start to overlap and some of the material starts to rupture, i.e. break away. In the steady-state period, the material loss through rupture is in a balanced state. As material is removed, new material becomes exposed to cavitation damage. In the deceleration period, if it is reached, the geometry of the material surface becomes so complex that air and vapor remain in the cavities in the material, thus potentially damping cavitation impacts and decreasing damage.

There are various methods for assessing a material's resistance to cavitation erosion. The ASTM G-32 standardized vibratory cavitation apparatus creates a cavitation cloud in stationary liquid with a vibrating horn (ASTM G32-10, Standard Test Method for Cavitation Erosion Using Vibratory Apparatus [10]). Hattori et al. [11-13] used this method to compare the erosion rates of a wide range of different metals. Kendrick, Light, and Caccese [14] used it to compare metals and composites. The ASTM G-134-95 cavitation testing apparatus provides a high-speed liquid jet that penetrates a static liquid. Cavitation occurs in the turbulent structures in the shear layer between the jet and the static liquid [15]. Soyama and Futakawa [16] compared multiple metals and several other materials using this method. Karimi [17] studied the cavitation erosion resistance of a duplex stainless steel with a vortex cavity generator.

Although many materials have been extensively tested with the ASTM G-32 static liquid testing method, few have been tested with hydrodynamic methods, as such methods generally require a larger test setup and more complex test setup. The reasons for studying cavitation erosion resistance in a hydrodynamic testing rig, rather than in a static liquid, have been highlighted by Karimi and Avellan in [18] and by Chahine et al. in [15]. In a vibratory cavitation apparatus, such as the ASTM G-32, the cavitation bubbles are all virtually the same size and the cavitation damage is distributed evenly and statically over the whole sample. This means that the cavitation mostly attacks the weaker material phases. In contrast, the hydrodynamic methods produce both different-size bubbles and flow vorticity effects, as well as other interactions with the liquid flow. For these reasons, it is often regarded that a hydrodynamic method, such as was used in this study, provides a better comparison of materials than the static liquid method.

In their fatigue erosion model, Fortes-Patella et al. [19] categorized the fatigue mechanism in cavitation erosion as low-cycle fatigue. Low-cycle fatigue occurs when plastic deformation occurs with each loading, so that material failure happens after a relatively low number of loading cycles [20]. Balyts'kyi and Chmiel [21] found a correlation between cavitation erosion fracture and the low-cycle fatigue resistance of steel alloys. Aboul-Kasem, Emara, and Ahmed [22] studied the particles removed from the material at different stages of the cavitation erosion process using scanning electron microscopy (SEM). Their study also showed that the erosion mechanism is due to fatigue and that the shape and size of the removed particles changes as the erosion shifts from the incubation period to the mass loss period.

In this study, the materials from three Francis turbines were tested: one low-alloy steel and two different stainless steels (referred to here as stainless steels 1 and 2). The test setup was the PREVERO high-speed cavitation tunnel [23]. The tunnel creates an axisymmetric cavitation erosion pattern. The resulting cloud cavitation is very similar to that in a hydrofoil, but with a higher intensity. Franc et al. [24] used the cavitation tunnel to study the cavitation erosion of a 7075 aluminum alloy, a C95400 nickel aluminum bronze alloy, a 304L stainless steel and a A2205 duplex stainless steel, so the materials in this study were compared to those. Deplancke et al. [25] have studied the erosion of ultra-high molecular weight polyethylene coatings, using the same operating parameters as Franc et al. [24], and they found that such coatings are highly resistant to cavitation. This type of coating could protect against cavitation in hydro machines, if it were economically feasible.

Material microstructure was attempted to be revealed by polishing, etching and observing with an optical microscope. Scanning electron microscope (SEM) imaging was used to study the cavitation erosion mechanisms and to pinpoint how the erosion evolves. All three tested materials were observed after they had been subjected to cavitation erosion. The images were taken from different locations and at different magnifications, allowing an overview of the erosion mechanisms at different stages of the erosion to be obtained, as all the stages of erosion coexisted in the eroded sample, depending on the location of the observed region. The SEM images also allowed the resulting cracks and removed particles to be studied in detail.

2.   Experimental Setup

The experiments were carried out in a high-speed cavitation tunnel, an image and a schematic of which is shown in Fig. 2, below. The principle is that 20-mm-thick sample discs of 100 mm-diameter were placed in the radially diverging test section. The sample disc thus acts as an opposing wall onto which the inlet nozzle directs the incoming flow. The incoming flow stagnates in the middle of the sample and then follows the radially diverging channel, which has a smaller cross-section area than that of the inlet nozzle. Here, the flow velocity reaches its maximum and the static pressure its minimum. This is where cavitation is initiated (inception). As the channel diverges, the flow velocity decreases, the static pressure increases and cavitation closure occurs.

The cavitation number in the tunnel is defined in Eq. 1:

$$\sigma = \frac{P_d - P_v}{P_u - P_d} \qquad\qquad (1)$$

where:

P_d = pressure downstream of the test section, Pa,
P_u = pressure upstream of the test section, Pa,
P_v = liquid vapor pressure, Pa.

The cavitation number in this study was 0.87, corresponding to an upstream pressure of about 4 MPa and a downstream pressure of about 1.86 MPa. The downstream section is pressurized by nitrogen gas, and a pump linked to a frequency transformer is used to control both the upstream pressure and the flow velocity in the tunnel. Downstream pressure may be set between ambient pressure and about 3 MPa and the maximum upstream pressure is 4 MPa. Similar cavitation tunnels can be studied in more detail in [6; 23; 26]. Fig. 2 presents the overview and schematic of the cavitation tunnel, along with the material sample and sample holder.

The test section consists of an inlet nozzle with a 16 mm diameter, followed by a radially diverging channel with a 2.5 mm thickness. The cross-section area of the channel drops by a factor of 1.6 at the beginning of the radially diverging part. This is where cavitation begins. The cavitation bubbles collapse somewhere between 19 mm and 32 mm radial distance from the center of the sample, with the maximum erosion occurring at a distance of 22 mm from the center.

The main components of the cavitation tunnel are the downstream tank, the pump and the test section, as presented in Fig. 2. The downstream tank is pressurized by a separate pressurization tank above the downstream tank. The tunnel is filled with water so that the pressurization tank is almost full; nitrogen gas is added from above through a pressure regulator. The pressure regulator controls the downstream pressure and thus the overall pressure level of the tunnel. The pump, which is located below the tunnel, increases the upstream pressure. The upstream pressure and the flow speed are controlled by changing the pump rotation speed. Most of the pressure drop occurs in the test section when the tunnel is in a cavitating state.

Three Francis turbine runner blade materials were tested: one low-alloy steel and two stainless steels (named low-alloy steel and stainless steels 1 and 2). All of the turbines in question were cast, but the exact details of the manufacturing process of the runner blades or the material samples are the manufacturers' confidential knowledge. The low-alloy steel sample was cut from an old turbine blade, as well as stainless steel 1. Stainless steel 2 was a separately cast sample, cast along with the turbine blades. All cutting was water jet cutting, so it was assumed that any changes in the microstructure due to sample manufacturing was insignificant. Initial polishing and evening of the surface was done by rotating sand paper grinding, with water added on the paper. Any major heating of the sample was thus avoided.

The samples were first mirror polished so that the surface was subject to as little initial strain as possible. the surface of the sample had to be virtually untouched in order to measure the cavitation incubation period as accurately as possible. To achieve a mirror-polished surface, successive diamond pastes with grain sizes of three μm and one μm were used with rotating polishing tissues. The surface was finished off using a colloidal silica suspension with a grain size of 0.03 μm, and then with yet another type of rotating polishing disk.

As the sample mass was large compared to the mass of the eroded material (1.2 kg compared to only a few grams), it would be difficult to accurately measure the mass loss due to cavitation erosion by weighing. For this reason, the volume and mass loss were defined through profile measurements. The evolution of the erosion was typically measured at four- to five-hour intervals with a contact profilometer (Taylor Hobson Form Talysurf 50) with a 2-μm spherical diamond point providing the contact with the surface. The erosion evolution could be calculated from these surface profiles, which were measured along a radial line running from the center of the sample center to its outer edge.

Initially, four profiles for each measurement were taken for the low-alloy steel sample, but this was later found to be inadequate because the erosion evolution had some discrepancies within one individual sample, so eight profiles were used for the later measurements. Eight profiles had been used for the stainless steel samples right from the start, as eight corresponded to the eight different azimuthal angles of the sample (see Fig.2 for visualization). In order to minimize potential errors, each profile was measured five times along parallel lines, each of them one μm apart, and then these values were averaged out to produce one profile. The samples underwent erosion until the maximum measured penetration depth in at least one profile reached about 500 μm. This took about 25 hours for the low-alloy steel, and about 65 hours for both the stainless steels.

The surfaces of the fully eroded samples were analyzed with an SEM (Leo S440). In order to form an accurate estimation of all the erosion mechanisms in the material, a great variety of images were taken with from 20 to up to 5000 times magnification (20 X to 5000 X) from different areas of the sample, including those areas with little to no erosion, up to the maximum erosion.

A high strain rate is typical in cavitation impacts [27]. The material parameters for the samples were studied with split Hopkinson pressure bar testing, which is a common testing method for stress-strain relationships with a high strain rate. A strain rate of 2000 1/s was used for all the steels in this study, i.e. the low-alloy steel and the stainless steels 1 and 2. As the strain rate is not constant in the plastic region of the samples, Young's modulus is not measurable with this method, so only the yield stresses were obtained and used to compare the materials.

3.   Calculating Steady-state Volume Loss Rate

Ten to twenty profiles were obtained for each azimuthal angle for each of the sample discs, each corresponding to an instant of time in the erosion process. Fig. 3 shows the erosion evolution as a function of time for the low-alloy steel sample with an azimuthal angle of 0°. The maximum penetration depth varies through the different azimuthal angles for the same sample, but is always located in the same radial location, as the erosion pattern is axisymmetric.

The first profile plotted In Fig.3 shows the transition area between the incubation and acceleration periods that occurs after 46 minutes of exposure to cavitation. The erosion on the sample is visible to the naked eye, and in the measured profiles it appears as surface roughness. The blue curve shows the erosion after 25 hours (1500 minutes), which was the total exposure time of the low-alloy steel and corresponds to a penetration depth of about 750 µm in the sample surface for the azimuthal angle of 0° (about 450 µm for angles 90° and 270°). The initial surfaces, presented in Fig. 4, were virtually flat compared to the advanced erosion stages.

The initial profiles in Fig. 4 are only for one azimuthal angle, but the profiles for the other angles are of a similar order of magnitude. The initial profiles were separated from the subsequent ones, although this procedure has only a marginal effect, as the roughly half-micrometer fluctuations are negligible compared to the up-to-700 micrometer penetration depths. Values above zero in depth were observed for all the materials especially in the incubation period. This is due to the piling up of the eroding metal due to cavitation impacts. This is expected in materials with a high ratio between the Young's modulus and the yield stress, such as most metals [7].

As cavitation is assumed to be axisymmetric in the test section, one would assume an axially-uniform erosion rate in the disk. To mitigate possible anomalies in the axisymmetricity of the erosion, the stainless steel samples were turned 90 degrees in the sample holder after each profile measurement. This procedure was introduced after the experiments with the low-alloy steel, as non-uniformities had been observed in these. Even with this procedure, the erosion depth was not equal in all the sample azimuthal angles. Fig. 5 (a-c) shows photographs of the tested sample materials after their respective full exposure times.

The volume loss at a given time for a given sample was calculated from the erosion profiles as shown in Fig. 4. To calculate the total volume loss over the sample, the depth value for each point was multiplied by the circumference. This meant that the volume loss was calculated for each profile under the assumption that the erosion profile would be the same across the whole sample. The average volume loss was calculated from the profiles (either 4, or 8). Finally, the mass loss was calculated by multiplying the volume loss by the material density.

4.   Results

4.1   Material properties

An external operator tested the chemical composition of the materials and these are listed in Table 1.

Material	Fe	C	Cr	Si	Mn	P	S	Ni	Mo	W
Low-alloy steel	98.69	0.205	0.0051	0.205	0.551	0.033	0.028	0.026	0.0032	0.0077
Stainless steel 1	80.00	0.046	13.80	0.238	0.726	0.026	0.014	4.385	0.201	0.219
Stainless steel 2	81.67	0.02	12.6	0.45	0.58	0.025	0.005	4.2	0.45	-

Table 1. Material chemical properties. The element contents are expressed as mass percentage.

The materials actually contained minor traces of several other elements, but these were irrelevant and have been excluded from Table 1. The materials' mechanical strength was studied with split Hopkinson pressure bar testing, as cavitation impacts tend to have a high strain rate. The stress-strain curve of a split Hopkinson pressure bar test is similar to that of conventional compression tests. However, the strain rate changes significantly in the elastic region, and because this impeded the accurate calculation of the Young's modulus, the yield stress was used. The yield stress is a significant parameter for determining whether a cavitation impact has damaged a material [28]. The yield stress may be extracted from the stress-strain curves by fitting a linear equation to both the elastic and the plastic part of the curve and then finding the intersection of these equations. The yield stresses at 2000 1/s strain rate for all three steels tested in this study are listed in the next section, in Table 2. For the comparison materials, the values for the yield stresses are taken from the literature on conventional compression testing. The conventional pressure test value is also listed for the low-alloy steel, but there were no listed values for the two stainless steels.

To characterize the material microstructure, the stainless steel samples were polished, etched and then studied through optical microscopy. Two examples of the microscope images are presented in Fig. 6 (a-b). The microstructure study concentrated only on the two stainless steels, as the low-alloy steel was considered an outdated turbine material, and it was only used for erosion rate comparison.

According to the optical microscope analysis, stainless steel 1 in Fig. 6 (a) is fully martensitic, with small amounts of carbides and other precipitates, as well as larger slag inclusions. The precipitates (possibly carbides) are too small to properly resolve by optical microscopy. The microstructure of stainless steel 2 in Fig. 6 (b) is predominantly martensitic, with a small amount of residual δ-ferrite and carbides and other precipitates, which have a bimodal size distribution. The dark lines in Fig. 6 (a) emerge from the prior austenite microstructure. They were not found in the other sample, both due to the etching treatment not being optimal for the material and the apparently much larger prior austenite grain size.

The notable difference between the microstructures is the considerably finer prior austenite grain size of stainless steel 1, measured as 37 μm, with a standard deviation of 10 μm, using the mean lineal intercept method as defined by ASTM E-112 Standard Test Methods for Determining Average Grain Size [29]. The prior austenite boundaries of the specimen stainless steel 2 could not be resolved. However, based on the visual observation of block and packet size and the configuration of the lath structure the prior austenite grain size of stainless steel 2 is much larger, by approximately an order of magnitude. The prior austenite grain size has been shown to correlate with martensite packet and

block size [30], which in turn has a negative correlation with strength. It has been shown that impact resistance and plasticity are particularly sensitive towards prior austenite grain size [31; 32] possibly explaining the better resistance of stainless steel 1 towards cavitation impacts.

4.2   Steady-state Erosion Rate

The volume loss of the eroded materials as a function of time is presented in Fig. 7. The three samples tested in this study, i.e. the low-alloy steel and stainless steels 1 and 2 are presented, as are two samples each of the other materials tested by Franc et al. [24]. Their samples were smaller than those used for this study, as they were fitted to a sample holder that holds eight samples at a time. Their small 16-mm-diameter disks were eroded simultaneously, but for ease of comparison, the erosion of Franc et al.'s small disks was calculated as if they covered the same area as our large disks.

The volume loss curves of the low-alloy steel and both samples of the 7075 aluminum alloy follow almost the same line, these being the fastest to erode. As some of the samples had eroded more than the others, defining the steady-state erosion rate from only the final erosion rate is not a fair comparison. The volume loss rate seems to fluctuate even at the relatively steady states of erosion, as presented in Fig. 8. For this reason, the steady-state volume loss rate is rather difficult to define. Therefore, a decision was made to define the volume loss rate as the average of all the volume loss rates between 50 mm^3 and 100 mm^3.

The incubation time was not used in comparing the materials in this study, because the variance between similar materials was too great, so its effects were removed by linear curve fitting to the linear part of the volume loss curves in Fig. 7, and then defining the x-axis intersection of the linear fit. To define the average volume loss rate between 50 mm^3 and 100 mm^3, a 4th order polynomial function was fitted to the volume loss data. The steady-state volume loss rate was calculated as in Eq. 2:

$$V_{lossrate} = \frac{100\ mm^3 - 50\ mm^3}{t_{100} - t_{50}} \qquad (2)$$

where:

t_{100} = time when erosion volume is 100 mm^3, s,

t_{50} = time when erosion volume is 50 mm^3, s.

The values for t_{100} and t_{50} are instants interpolated from the polynomial fitted to the experimental points when the volume losses are 100 mm^3 and 50 mm^3, respectively.

As previously explained, the samples in our study were a different size to those used in the comparison study. The average steady-state erosion rates and the high strain rate yield stresses for all of the compared materials are presented in Table 2.

Material	Steady-state volume loss rate (mm³/h)	Steady-state mass loss rate (mg/h)	Material density (kg/m³)	Yield stress (MPa)
Low-alloy steel	8.95	69.79	7800 [33]	228, 259 at (2000 1/s)
Stainless steel 1	1.79	13.93	7800	452 at (2000 1/s)
Stainless steel 2	2.72	21.23	7800	477 at (2000 1/s)
7075 Aluminum alloy sample 1	7.88	22.12	2810 [34]	103-145 [34]
7075 Aluminum alloy sample 2	8.18	22.99	2810 [34]	103-145 [34]
A2205 Stainless steel sample 1	2.21	17.27	7820 [35]	448 [35]
A2205 Stainless steel sample 2	1.31	10.25	7820 [35]	448 [35]
304L Stainless steel sample 1	3.29	26.29	8000 [36]	210 [36]
304L Stainless steel sample 2	2.83	22.64	8000 [36]	210 [36]
C95400 Nickel aluminum bronze sample 1	2.86	21.34	7450 [37]	205 [37]
C95400 Nickel aluminum bronze sample 2	2.30	17.17	7450 [37]	205 [37]

Table 2. Steady-state mass loss and volume loss rates of the studied materials.

The material densities presented in Table 2 are general values, as they were not measured for the materials or individual samples used in our study. For the two stainless steels, densities are assumed to be the same as that of the low-alloy steel. In the present work, the volume loss rate is preferred over the mass loss rate for defining the erosion rate, thereby reducing the importance of defining the densities accurately.

A lower steady-state volume loss rate indicates higher cavitation erosion resistance. Using this metric, our results show that the low-alloy steel has the poorest resistance to cavitation, falling into the same category as the 7075 aluminum alloy in terms of volume loss rate. The 304L stainless steel has a moderate resistance to cavitation and stainless steel 2 falls into the same category as the C95400 nickel aluminum bronze alloy. Stainless steel 1 and A2205 stainless steel are both superior to all the other tested materials.

The low-alloy steel has a lower yield stress than the two stainless steels, with a strain rate of 2000 1/s. The low-alloy steel was also tested in a conventional compression test, so both values are presented in the table. The other materials were not tested for their yield stresses in this study, so those values are taken from the literature. The three tested materials are not comparable to the rest of the samples, as they were measured at different strain rates. However, they may be compared separately. The yield stresses for stainless steels 1 and 2 are almost equal, although they have different erosion rates. For the other materials, the yield stresses correlate with the erosion rates, so that a higher yield stress corresponds to a lower steady-state erosion rate. It is worth noting that the low-alloy steel has a higher yield stress than the aluminum alloys (if one ignores the different strain rates).

It is noticeable that the low-alloy steel suffered greater mass loss than the 7075 aluminum alloy. In addition, the low-alloy steel started to rust during the experiments as it was in contact with water. This may also have contributed to its high erosion rate. As the metal oxidizes, it degrades the quality of the surface, which is then removed by the cavitation, continuously exposing fresh surface to the water, thus increasing the corrosion rate [38].

An interesting detail that surfaced from this comparison of the two turbine runner stainless steels is that the one which performed better came from a Francis turbine designed in the 1970's, while the worse-performing one came from a much more recent Francis turbine design (2010s). The low-alloy steel was from a turbine constructed in the 1930's, which was later decommissioned. This detail shows that, at least in this case, cavitation erosion resistance was probably not a known parameter when making material choices at that time. Shifting from steels to stainless steels seems to increase the metal's resistance to cavitation erosion significantly.

As mentioned in Section 3, the erosion rate is dependent on the azimuthal angle, as the evolution of the erosion is not perfectly uniform. This non-uniformity may not have been apparent with the small samples used in the experiments by Franc et al. [24]. An example of the non-uniformity of erosion evolution is presented in Fig. 9, in which eight curves for eight different azimuthal angles are presented.

The reason for the differences in the erosion rates could be due to differences in the composition of the material within just the one sample. As cavitation is such a complex process, it is possible that even small differences in the sample's composition and microstructure would lead to different erosion rates. These may that persist even if the erosion process goes on for a long time. The erosion rates do not seem to fall clearly around a single value as the erosion evolves. The strength of cavitation erosion in the cavitation tunnel is assumed to be axisymmetric, and even if this is not absolutely true, turning the sample between each testing intervals should have negated any non-axisymmetrical effect.

To study the differences in steady-state volume loss rates within one sample, the rates were calculated using the same method as before for the four azimuthal angles for the low-alloy steel and for all eight azimuthal angles for the two stainless steels. The resultant steady-state volume loss rates are presented in Table 3.

Material	Rate 1 (mm³/h) 0°	Rate 2 (mm³/h) 45°	Rate 3 (mm³/h) 90°	Rate 4 (mm³/h) 135°	Rate 5 (mm³/h) 180°	Rate 6 (mm³/h) 225°	Rate 7 (mm³/h) 270°	Rate 8 (mm³/h) 315°
Low-alloy steel	11.62		5.44		12.38		3.63	
Stainless steel 1	1.40	1.70	2.02	2.24	1.52	1.58	2.30	2.21
Stainless steel 2	4.02	2.94	3.02	2.95	3.56	2.66	2.43	2.27

Table 3. Steady-state volume loss rates of the studied materials for different sample azimuthal angles. The sample azimuthal angle is presented in degrees so that 0° degrees means north and 180° degrees means south on the circular sample surface.

The differences between the sample azimuthal angles in the steady-state volume loss rates are significant, especially for the low-alloy steel. The low-alloy steel was not turned between measurements, so non-uniformity in the erosion potential of the cavitation tunnel might be a major reason in the differing erosion rates. The erosion rate follows a pattern in which a relatively high value always has a counterpart falling into the same diagonal. This raises the question as to whether the samples were completely isotropic. It was initially assumed that they were, as they were manufactured by casting and were cut using methods that do not overly heat the sample. Small differences in the microstructure are expected, as the material solidifies at a different rate depending on the location inside the cast. The fact that the steady-state volume loss rate fluctuates significantly depending on the azimuthal angle clearly indicates that the cavitation erosion resistance of a material cannot properly be defined without looking into its microstructure.

4.3   Scanning Electron Microscopy

Scanning electron microscope (SEM) images with various magnifications were taken of the sample surface in order to make this a qualitative study. Fig. 10 (a-c) shows three panoramic images of the eroded areas of the studied materials taken with a 20 X magnification. These images show the center of the sample on the left and the right is towards the edge of the sample.

Although the areas of maximum erosion in the images in Fig. 10 are not exactly aligned, in the actual samples the erosion occurred in the same radial location. The discrepancy is due to the image processing, as the panoramic images were constructed from multiple smaller images.

The erosion in the low-alloy steel in Fig. 10 (a) begins abruptly compared to the stainless steels in Fig. 10 (b-c). The erosion in the downstream region after the maximum erosion depth is about 6 mm long for all three materials, while in the upstream region, although it is approximately the same for the stainless steels, it is only about 2 mm long for the low-alloy steel (based on visual observations from these images). The pits and erosion in the upstream region of the stainless steels consist of individual pits and surface roughness, placing the stage of erosion in those regions as somewhere between the incubation and acceleration periods. The downstream regions of all the samples are

rougher than the upstream regions, putting these regions in the acceleration, or even the steady-state, period of erosion evolution.

The exposure time of the low-alloy steel was much lower than that of the stainless steels. As the upstream damage to the stainless steels consists of single pits and surface roughness, it is concluded that the rate of cavitation impacts is much lower upstream of the maximum depth than it is in other regions. Because of the low-alloy steel's lower exposure time, there might be less time for such individual pits to form in the upstream region.

Figs. 10 and 11 show SEM images of the low-alloy steel at a greater magnification (200 X). The evolving cracks can be seen everywhere, so it may be assumed that these cracks, and any subsequent ruptures, would be a major factor in the rate of material loss, as expected.

In Fig. 11, the eroded surface is uneven and the 'valleys' of the erosion pits seem to be deep compared to the surrounding 'mountains'. The actual depth of the pits could not be defined using the SEM. This image with 200 X magnification shows the overall structure of the highly eroded surface, but it does not tell us much about the erosion mechanisms. When a chunk of the material is removed by rupture, it leaves a smooth surface behind, as can be seen in Fig. 12. The smooth surface is then attacked by subsequent cavitation impacts, leaving small pits that eventually start to overlap.

The 1000 X magnification in Fig. 12 offers more insight into the erosion mechanisms. The surface in the middle of the image is relatively smooth, with some small widely-spaced pits in it. The diameter of the small pits is in the range of one μm, which corresponds to small cavitation impacts. One possible cause for such a smooth surface could be that a relatively large chunk, microscopic in actual size, of material was removed quite recently. Once the large chunk had been removed, the new smooth surface was only exposed to cavitation for such a short time (the time remaining in the test period) that only the small individual pits are seen.

Fig. 13, at 2000 X magnification shows the progression of a crack front.

A series of lines, identified by the red arrows, are visible in Fig. 13. As each new impact of sufficient amplitude hits the surface of the material in the vicinity of the crack, the crack front is supposed to jump from one line to the next. This crack propagation ends up with the removal of a micro-piece of material that makes the plane of the propagated crack visible, as can be seen in Fig. 12. This pattern is commonly associated with low-cycle fatigue, which supports the idea that cavitation erosion at the intensity generated in the cavitation tunnel is most probably due to low-cycle fatigue.

Fig. 14 shows a well-developed crack propagation process with a presumably soon-to-be-removed chunk of material.

The image with 2000 X magnification in Fig. 14 offers some insight into the removal of individual chunks of material. The chunk in the middle of the image is surrounded by large cracks and it is covered with plastic deformation resulting from cavitation impacts. If the erosion were to continue, the cavitation impacts hitting the chunk of loosened material would eventually cause it to break away.

These observations all support the results and assumptions made in [19; 21; 22], which is that the erosion mechanism in the mass loss period is probably caused by low-cycle fatigue. Virgin surfaces

with several small pits showing where tiny particles have subsequently been removed were found throughout the samples, as were cracks and soon-to-be- removed chunks.

5.   Conclusions

Steady-state cavitation erosion rates were studied for one low-alloy steel and two stainless steels (stainless steel 1 and 2). They were compared to those of 7075 aluminum alloy, C95400 aluminum bronze alloy, 304L stainless steel, and A2205 stainless steel. Steady-state volume loss rate was defined as the average volume loss rate between 50 mm^3 and 100 mm^3 total volume loss, to mitigate fluctuation and to provide a fair comparison of the materials. It was shown that to properly assess steady-state erosion rate, one has to average several erosion processes through the sample. The stainless steels were samples from turbines that are of a type that is still in use, so they are relevant in the field of turbine design.

The low-alloy steel had the poorest cavitation erosion resistance, along with the 7075 aluminum alloy. In this study, 304L stainless steel, C95400 aluminum bronze alloy, and stainless steel 2 had a better resistance than the other materials, while A2205 stainless steel and stainless steel 1 had the highest cavitation erosion resistance. It was found that the erosion rates differ significantly even within one sample. This means that assessing a single value for cavitation erosion resistance is problematic, as factors such as small differences in the local material composition or microstructure might change the erosion rates significantly. Even minor anisotropies in the sample material might be the cause of significantly differing erosion rates, as it was observed that the erosion rates are either high or low along the same diagonal in a circular sample. This means that in hydro machines, cavitation erosion rates may also differ greatly, depending on how, for example, the casting process leads to different grain sizes in the machine.

Materials with low steady-state erosion rates, and therefore high cavitation erosion resistances, generally had a higher yield stress. The yield stress, however, cannot be used alone to estimate the erosion rate, as stainless steel 2 had a slightly higher yield stress than stainless steel 1, for example, but it also had a higher erosion rate. Furthermore, the low-alloy steel had a higher yield stress than the 7075 aluminum alloy, but both materials eroded at the same rate. This was probably due to the combined effect of corrosion and cavitation erosion.

The material microstructure analysis showed that stainless steels 1 and 2 consists of almost 100 % martensite and that the first one has a significantly smaller prior austenite grain size. The prior austenite grain size is related to the impact strength and plasticity, so this could explain the difference in erosion rate between these two martensitic steels.

SEM images were taken from three eroded samples and they were analyzed to observe the erosion mechanisms. The images showed the dominating erosion mechanism to be most probably low-cycle fatigue. Virgin areas were found, with recently removed material and pits resulting from plastic deformations. Cracks and presumably soon-to-be-removed chunks of material were observed throughout the samples. So called "beach marks" were also found, indicating towards low-cycle fatigue.

Acknowledgements

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Figure 2. The cavitation tunnel used in this study, with schematics and the sample. The surface profiles were measured in the eight measurement zones or lines, one profile for each. The zones were named so that 0° corresponds to "north"; 45° to "northeast" and so on.

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