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Cavitation erosion testing of different cavitation-resistant materials and coatings using the cavitating jet method

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Abstract. An experimental test circuit was built with submerged nozzle with diameter 1.2 mm and inlet pressure 200 bar. Several specimens of different cavitation resistant materials used for hydraulic turbines (e.g. 13Cr4Ni) and coatings (e.g. tungsten and chromium carbides) were tested. Cavitating jet tests proved to be very efficient, sufficient cavitation erosion was obtained within 90 minutes. Comparisons between different materials were based on microscopic mapping of the eroded surfaces and SEM visualizations. Finally comparison between cavitating jet test and hydrodynamic cavitation tests using the orifice is presented. Duplex steel weld deposit proved to be the most cavitation resistant material

1. Introduction
Cavitation is a typical phenomenon connected with operation of hydraulic machines, especially in off-design operating conditions. It causes noise, increased level of vibrations, flow instabilities and pressure pulsations. From the material point of view, the most dangerous effect is cavitation erosion, i.e. erosion of the surfaces due to repeated collapse of cavitation bubbles. Erosion process increases surface roughness and thereby decreases hydraulic efficiency. If neglected it can threat structural stability and lead to material fractures.

While it is priority to eliminate cavitation already in the design stage (proper shape of blades and blade channels and respecting required NPSH of the hydraulic machine), it is often the case that cavitation cannot be completely avoided. Request on operation of hydraulic turbines far from the design point inevitably leads to admitting operation with presence of at least partial cavitation. Therefore cavitation resistant materials are selected for manufacture of the hydraulic turbine runners. However even these materials suffer from cavitation erosion after long exposure to imploding cavitation bubbles. Then, repair of the core material with different coatings or weld deposits is necessary. Present paper brings results of cavitation erosion tests of such materials.

2. Methods for cavitation erosion testing
Cavitation erosion testing of materials is described in several standards, nice overview of the methods is presented in [1]. The most frequently used method is the ultrasonic apparatus (standard ASTM G32, [2]), where the eroded specimen is held in stand-off distance 0.5 mm from the vibratory horn, which oscillates with frequency 20 kHz and amplitude 50 µm. Such method was applied for example in [3] to...
perform cavitation resistance tests of a whole database of stainless steels. Fast motion of the horn induces cavitation bubbles, which implode on the specimen surface. While this method provides very fast cavitation erosion, it is known that the mechanism of the erosion is different from the one occurring in real hydraulic machines. Ultrasonic apparatus tends to create bubbles of the same size and at precisely given frequency. The real hydrodynamic cavitation produces broadband spectrum of bubble sizes at various frequencies. Therefore different methods of cavitation erosion testing were employed in present paper.

2.1. Hydrodynamic cavitation induced by orifice
This method is based on scheme in figure 1. Water flowing through the orifice (diameter 20 mm) is accelerated and sudden pressure drop is induced in the constriction (“Bernoulli effect”) causing a phase change when saturated vapor pressure is reached. Resulting bubble cloud is carried downstream toward a specimen in shape of hydrofoil (figure 2), where the bubbles implode (leading edge of the hydrofoil is placed 90 mm downstream of the orifice edge). Mechanism of the cavitation erosion process is very similar that of in pump or hydraulic turbine.

For this purpose a hydraulic circuit was built, which consists of water tank, pipes (diameter 53 mm), circulating pump controlled by frequency converter and a test section. The test section is made of plexiglass to observe the bubble clouds, see figure 3. Pressure sensors are mounted upstream and downstream of the test section, induction flowmeter is placed at the pump outlet. Disadvantage of our circuit is absence of the vacuum pump, i.e. cavitation number can only be modified by flow rate. Pump speed, respectively the flow rate, was adjusted to obtain a cavitation cloud imploding on the specimen surface, see figures 3, 4. The cavitation number was:

$$\sigma = \frac{p_2 - p_v}{p_1 - p_2} = 0.225$$

where $p_1$ and $p_2$ are static pressure upstream and downstream of the test section and $p_v$ is the vapor pressure. Circuit enables to cool the water and run the tests 24/7 while adhering all safety rules (automated shutdown in case of overflowing, high temperatures, vibrations, etc.). The circuit proved to be very suitable for testing aluminium alloys, bronze, ceramic materials or carbon steels. However testing of cavitation resistant materials did not bring satisfactory results, even when running for 190 hours (almost 8 days). Only coating was hit by the imploding bubbles, almost no damage was observed on the stainless steel surface.

![Figure 1. Scheme of the test circuit with cavitation induced by orifice.](image1)

![Figure 2. Dimensions of the specimen.](image2)
2.2 Cavitating jet

Cavitating jet testing is described in ASTM standard G134-95 [4] and was applied for example in [5] to test different materials used for hydraulic turbines. In our case a test stand inspired by this standard was built, see figure 5. Water is supplied by piston pump with gas accumulator to suppress pressure pulsations, output pressure is 200 bar. Nozzle with 1.2 mm outlet diameter is via high-pressure hoses coupled to accumulator. Nozzle is submerged 6 cm under water level and emitted jet hits the specimen, which is in stand-off distance 20 mm from the nozzle. First, an experiment with aluminium specimen was carried out to optimize the stand-off distance in order to obtain maximum cavitation erosion. Specimen has dimensions 27x27x10 mm and is held on the table under water level in the basin, see figure 6. Time of the testing is 90 minutes.

Cavitation produced by cavitating jet is very similar to hydrodynamic cavitation in hydraulic machines. Compared to cavitation induced by the orifice this method is much more effective and offers significantly lower testing times. Cavitation bubbles and vortices of different sizes are induced by the nozzle. This method utilizes the fact that cavitation erosion aggressiveness scales with the seventh power of the jet velocity. In our case jet velocity is order of magnitude higher than in case of orifice induced cavitation.
Cavitation number is defined as:

\[
\sigma = \frac{p_2}{p_1} = 0.005
\]  

(2)

Where \(p_1\) is the absolute pressure supplied by the piston pump and \(p_2\) is absolute pressure at the nozzle exit (≈ atmospheric pressure).

3. Cavitation erosion testing

3.1 Materials tested

Material, which is most often used for hydraulic turbines, i.e. 13Cr4Ni, was employed as the core material for most of the tests. Different coatings applied using HVOF or plasma arc and based on carbides of tungsten and chromium were tested. It should be noted that these are not diffusion coatings.

Additionally also austenitic steel and duplex steel weld deposit were tested. Special cavitation resistant coatings (Cavitec, MeCaWear) were applied and supplied by Castolin. Because of the unacceptable time and results from the testing by cavitation induced by the orifice, only first three specimens were tested by both methods. Rest was tested only using the fast cavitating jet method.

Since we had access to advanced metallographic methods (3D digital light microscopes Olympus DSX510 a DSX110, scanning electron microscope TESCAN LYRA3 XMH, microhardness tester DuraScan-70 G5), mass loss was not measured and only microscopic metallographic properties were evaluated.

Table 1. List of all tested materials and coatings.

| Materials and coatings                  | Coating thickness (μm) | Impregnation layer thickness (μm) | Methods of cavitation erosion testing |
|----------------------------------------|------------------------|----------------------------------|-------------------------------------|
| 13Cr4Ni, no treatment                  | -                      | -                                | orifice, jet                        |
| 13Cr4Ni + WCCoCr coating + impregnation| 404.3                  | 79.2                             | orifice, jet                        |
| 13Cr4Ni + WCCoCr coating (no impregnation) | 451.0                  | -                                | orifice, jet                        |
| 13Cr4Ni +Cr3C2+25NiCr+ impregnation    | 410.6                  | 81.2                             | jet                                 |
| 13Cr4Ni+WC+Cr+Ni+ impregnation         | 463.1                  | 75.0                             | jet                                 |
| 13Cr4Ni+13Cr+Fe+impregnation           | 1017.5                 | 132.5                            | jet                                 |
| Cavitec weld deposit                   | 524-953                | -                                | jet                                 |
| 13Cr4Ni +MeCaWear300 surface treatment | -                      | 126.6                            | jet                                 |
| austenitic steel AISI 321 (1.4541)     | -                      | -                                | jet                                 |
| 13Cr4Ni+duplex weld deposit            | 6003.1                 | -                                | jet                                 |
| Zander 4332 W (1.4332)                 |                        |                                  |                                     |

Impregnation in all cases, where impregnation was applied, was Metcoseal URS.
### Table 2. Cavitation erosion damage characteristics from the cavitating jet testing.

| Materials and coatings                                      | Depth of the damage (µm) | Diameter of the damage in impregnation layer (mm) | Diameter of the damage in coating/material (mm) |
|------------------------------------------------------------|---------------------------|-----------------------------------------------|----------------------------------------------|
| 13Cr4Ni, no treatment                                      | 33.4                      | -                                             | 2.4                                          |
| 13Cr4Ni + WCCoCr coating + impregnation                    | 550.5                     | 4.6                                           | 1.6                                          |
| 13Cr4Ni + WCCoCr coating (no impregnation)                 | 509.3                     | -                                             | 2.9                                          |
| 13Cr4Ni + Cr₃C₂+25NiCr+ impregnation                       | 375.9                     | 4.6                                           | 1.6                                          |
| 13Cr4Ni + WC+Cr+C+Ni+ impregnation                         | 412.4                     | 4.6                                           | 1.8                                          |
| 13Cr4Ni+13Cr+Fe+impregnation                              | 522.0                     | 4.0                                           | 1.7                                          |
| Cavitec weld deposit                                       | 110.9                     | -                                             | 2.3                                          |
| 13Cr4Ni + MeCaWear300 surface treatment                    | 56.6                      | 8.8                                           | 2.2                                          |
| Austenitic steel AISI 321 (1.4541)                         | 46.5                      | -                                             | 1.7                                          |
| 13Cr4Ni+duplex weld deposit Zander 4332 W (1.4332)         | 5.3                       | -                                             | 2.3                                          |

Whole scope of the evaluation methods is illustrated for the first specimen (13Cr4Ni, no surface treatment), which was taken as a reference case. 13Cr4Ni is martensitic low carbon steel with hardness 220 HV. As it has already been mentioned no erosion was apparent for cavitating orifice testing, therefore most of the presented pictures are from cavitating jet tests. Quantitative comparison of the different materials and coatings is based on the evaluation of the erosion depth, diameter of the eroded impregnation layer and eroded surface respectively for cavitating jet test.

**Figure 7.** Testing of 13Cr4Ni specimen by the orifice induced cavitation.

**Figure 8.** Cavitating jet test of 13Cr4Ni specimen.
Figure 9. Cavitating jet test of 13Cr4Ni specimen, 600x magnification.

Figure 10. 3D surface reconstruction (cavitating jet test, 13Cr4Ni).

Figure 11. Cavitating jet test of 13Cr4Ni specimen, 1150x magnification (SEM).

Figure 12. Cavitating jet test of 13Cr4Ni specimen, 11500x magnification (SEM).

Deep cracks and craters between the grains are visible. Surface has very sharp protrusions, result of the fracture on level of grains, very typical for cavitation erosion.
Figure 13. Cross-section of the eroded surface (13Cr4Ni, cavitating jet) and plot of the profile (depth-length).

Second specimen (13Cr4Ni + WCCoCr coating + impregnation) was selected as representant of specimens with coating and impregnation layer. All carbide based and impregnated coatings are non-diffusion coatings.

Figure 14. Cavitating orifice test of 13Cr4Ni + WCCoCr coating + impregnation.  

Figure 15. Detail of the leading edge after cavitating orifice test.

Even cavitating orifice testing was able, after 190 hours, to erode through the impregnation and coating, also the core material was also slightly touched by the erosion process.
Figures 16-19 show penetration of the cavitation through the impregnation layer and then through the coating, finally hitting the core material (13Cr4Ni) itself. It is interesting that erosion of the core material is higher than in case of the pure 13Cr4Ni material. It suggests that either there was a thermal influence of the core material during coating application or diffusion in the uppermost core material layer occurred. Very low cavitation resistance of the coating is apparent.
Finally, duplex steel weld deposit Zander 4332 W was selected as example of the most cavitation resistant material in the cavitating jet tests.

Figure 20. Cross-section of the eroded surface (cavitating jet, 13Cr4Ni + WCoCr coating + impregnation), plot of the profile (depth-length).

Figure 21. Cavitating jet test of duplex steel weld deposit Zander 4332 W.

Figure 22. Cavitating jet test of duplex steel weld deposit Zander 4332 W, 200x magnification.

Figure 23. 3D surface reconstruction: duplex steel weld deposit Zander 4332 W (cavitating jet test).
Figure 24. Cross-section of the eroded surface (cavitating jet, duplex steel weld deposit Zander 4332 W), plot of the profile (depth-length).

Duplex steel is combination of delta-ferrite (10%) and austenite (90%). It has fine-grained structure with hardness 262 HV. Thanks to its more ductile behaviour, compared to 13Cr4Ni, the plasticity reserve is depleted later for the duplex steel, which increases its cavitation erosion resistance.

4. Conclusion
Several conclusions can be drawn from the presented investigations:
- cavitating jet method provides reasonably fast response compared to cavitating orifice method
- non-diffusion coatings have very low resistance against cavitation erosion both in cavitating orifice and cavitating jet experiments. Moreover, the results were worse than in case of the core material (13Cr4Ni) alone.
- duplex steel weld deposit (Zander 4332 W) was the most cavitation resistant material tested. A recommendation can be drawn to use this material as the first choice for repairs of the eroded surfaces in hydraulic turbines.

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