OPTIMIZED MAINTENANCE SOLUTIONS FOR HYDROPOWER PLANTS

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Abstract:
Cavitation and erosion are well known wear mechanisms in hydropower plants. To fight against important wear rates on expensive machinery elements is a current subject of discussion.
Availability improvements through preventive and scheduled maintenance combined with an easy to repair approach are the main objectives of every hydropower plant manager.
Several efficient coating processes were developed to realize improved protection against cavitation and erosion, such as

- *HVOF*
- *Arc spaying*
- *Arc welding*
- *Cold polymeric coatings*

From our point of view, hydropower plants will have to optimize maintenance by elongating repair intervals and reducing excessive downtime. The mutual selection of the right coating system combined with an outstanding alloy design will achieve these objectives and satisfy these needs.

Introduction

Erosion and cavitation are the main wear mechanisms reducing the lifetime of machinery components in hydropower plants (Fig. 1). Erosion is a kind of metal cutting process due to highly sand loaded water. Most important factors influencing this wear type are the content, the mass, the hardness, the relative velocity and the angle of attack of the particles. Cavitation on the other hand is a form of surface fatigue. Cavitation is generally associated with high head and varying load and tailwater values. Both wear types, erosion and cavitation may occur at the same time and reinforce each other - examples are the inlet edges of pump turbines.

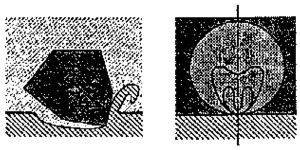

Figure 1. Schematic description of sand erosion and cavitation
[acc. to Dr. A. Karimi, IGA, EPFL Lausanne]

1. Brief background

The most common constructional steel used for turbine components is X5 CrNi 13 4. This martensitic material offers good strength, satisfying machinability, weldability and considerable resistance against erosion and cavitation. Yet combining all these different features it can only be a compromise to a certain extent.

Due to this reason there is an increased need for tailor made coatings which can improve the wear resistance against cavitation and erosion. Today a broad range of coatings is available, e.g. HVOF, Plasma, Arc spraying, welding and cold polymeric materials. HVOF, Arc spraying, welding and cold polymeric coatings are the preferred technologies for applying erosion and cavitation resistant coatings. A reduction of the repair and maintenance costs, decreasing revenue losses from excessive downtime and elongated service intervals are the final objectives of new developments in this area.

This paper presents both a Cavitec®, a cavitation resistant welding alloy and the latest trends in thermal spraying technology, especially in the field of HVOF and Arc spraying. Furthermore, the results of an experimental program comparing different erosion resistant alloys as well as several interesting applications of new coatings are shown. The summary gives a general overview of possible coatings on turbine components and an evaluation of different criteria which influence the right choice of the coating system and optimized alloying systems for erosion resistant coatings.

2. Cavitation resistant surface protection

Cavitation occurs to varying degrees throughout the wide spectrum of hydraulic machine types, sizes and ages. The compressive cavitation shocks produce local elastic and/or plastic deformation of metallic surfaces.

The repeated collapse in the same area provokes surface tearing or fatigue cracking depending on the stress intensity/yield strength ratio. The propagation of these cracks initiates the erosion process through the removal of small metallic particles from the exposed surface. During the initial period of cavitation exposure, the so-called incubation period, surface plastic or fatigue deformation progresses until surface cracking extends and small micron-size metallic particles are detached more and more frequently with a corresponding erosion-rate increase. The length of this incubation period depends on both cavitation and the material's resistance. It may be just a few minutes for softer metals in high intensity laboratory tests or as long as many months for high resistance alloys in industrial machines. When the penetration rate of surface erosion equals the ingression rate of the deformed layer, a steady state is reached with a constant erosion rate.

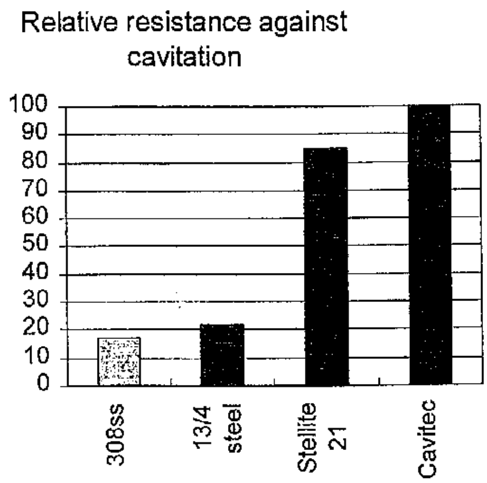

Figure 2 General comparison (jet cavitation and field experience) of Cavitec® with other alloys

Especially for higher intensity cavitation zones tailor made alloys are required. Hydro Quebec Canadian, a hydro power company, running some 300 generating units ranging in capacity from 1 MW to 350 MW, performed a systematic test program in its laboratories in order to find an optimized and still cost efficient cavitation resistant welding alloy. The starting point was with cavitation tests done with a vibratory ultrasonic cavitation test acc. ASTM G32-77 and a jet cavitation test rig. These tests already showed the excellent properties of a soft cobalt base alloy called Cavitec® [1].

Fig. 2 gives a general comparison of this material to other alloys. Cavitec shows a cavitation resistance at least up to five times higher than conventional stainless steels thus offering an obvious economical advantage of reducing the number of maintenance and repair downtimes [2]. Interesting is the fact that the laboratory tests acc. ASTM G32-77 gave much better improvement rates (up to 12) than the field tests (about 5), which seems to be related to the larger material volume deformed by each cavitation impact in larger turbines [3].

Table 1 gives some background information about Cavitec concerning analyses and microstructure. Cavitec can be best described as a high strain hardening austenitic stainless steel. The strain hardening mechanism and high work hardening rate are essentially influenced by controlled additions of cobalt, silicon and manganese. These alloy additions effectively reduce the stacking fault energy and import to the iron base matrix deformation characteristics similar to cobalt base alloys. So surface hardening and martensitic transformation, that means the austenitic γ-phase structure transforms under cyclic stress to an α-martensitic phase which results in a very fine deformation twinning by cavitation impacts, are the key factors in continuously regenerating under cavitation exposure an efficient surface barrier against cavitation attack.

C	N	Si	Co	Mn	Cr	Fe
0,20	0,20	2,50	9,00	9,50	17,00	Base
Microstructure: austenitic (γ), low stacking fault energy						

Table 1: Chemical composition [Wt %] and microstructure of Cavitec®

3. Thermal spraying against erosion

Thermal spraying is already state of the art for applying erosion and adhesion resistant coatings on hydroturbine components without any thermal effects in the base material. Yet recent developments have shown considerable improvements concerning coating quality, erosion resistance, repairability and economical efficiency. High pressure HVOF systems and new materials for Arc spraying offer the solution for critical erosion wear problems.

3.1 High Pressure HVOF Coatings

The High Pressure HVOF process is the latest development among the different HVOF systems and gives by far the highest gas and particles velocities, which results in dense coatings. This new High Pressure HVOF-system operates with combustion pressures up to 10 bar, that means more than two times greater than for conventional HVOF guns.

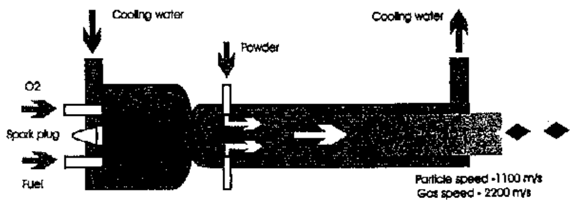

Fig. 3 Principle of High Pressure HVOF

Fig. 3 shows the principle of this new system. For erosion resistant coatings in hydropower components tungsten carbide cobalt chromium WC/Co/Cr coatings proved to be most successful (see chapter 4). The new High Pressure HVOF-system provides improved treatment of the powder particles from the time of radial injection in the gun during the flight over to the part and at impact into the coating. The powder is entrained in a more favourable environment (less oxidizing atmosphere) and has a shorter exposure time due to the high velocity. Thus, the original structure of the WC monocarbide is not changed into η-carbides which is likely to happen with conventional HVOF guns. The additional use of liquid fuels with these systems helps to increase the safety aspects and improves the relation of kinetic compared to thermal energy, thus avoiding thermal destruction of the carbides [4].

The coating consists therefore of a WC monocarbides in a Co-Cr matrix. The difference can be easily seen in the microstructure. Fig. 4a shows a strongly transformed WC-Co-Cr coating, Fig. 4b shows the same powder sprayed with a High Pressure HVOF - the transformation of carbides that means from WC monocarbides to brittle η carbides is much less. As a result such WC-coatings are more ductile which was proven by cavitation tests (see chapter 4). There are certainly several other important influence factors in the coating quality such as the structure of the powder for example, but still the system technology plays a major role in the

HVOF coating process. The latest step was the development of a mobile High Pressure HVOF which allows an in situ repair and which may be useful for turbine components with only small spots to coat or large turbines difficult to manipulate.

Fig. 4a Microstructure of WC/Co-Cr conventional HVOF-system, strongly transformed carbides

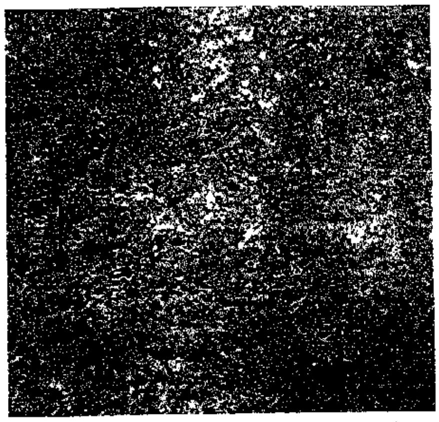

Fig. 4b Microstructure of WC/Co-Cr HVOF (1350 V) sprayed with HP-HVOF, only slightly transformed carbides

3.2 Arc Spraying

Arc spraying offers several advantages compared to flame spraying technologies which are a very high bond strength, higher deposit rates and denser coatings. Beside conventional 13% chromium steels new cored electrodes offer the possibility to create highly wear resistant coatings.

So called amorphous materials can be produced only as cored wires. During the arc spraying process such materials form amorphous phases which are highly resistant to erosion. Typically these materials are highly alloyed with chromium, boron and silicon. They do not offer the same properties as WC coatings, however, by building up higher coating thicknesses they can be an economical option to HVOF still offering good wear resistance. Chapter 4 gives the performance of such coatings in comparison to welding and HVOF

4. Experimental erosion tests

4.1 Sand erosion test

In order to characterize the behavior of each coating material against erosion, tests were performed on specimen with a special device developed by Dr. Christian Verdon at the Swiss Federal Institute of Technology of Lausanne at IGA (Institut de Génie Atomique, EPFL, Lausanne) [5].

The installation is a closed-loop circuit allowing to send a water jet against a cylindrical specimen. The water is mixed in an upper tank with a given quantity of sand. A high pressure pump allows the speed variation of the jet. The specimen is fixed on a frame and can be oriented with a chosen angle against the jet.

Many different systems exist to test coated specimen resistance against erosion. This circuit is easy and quick to use and allows to vary speed and angles on a very large range (5 to 120 m/s, 5 to 90 degrees).

After a first qualification with a speed of 65m/s and an angle of 15 degrees for many different coating materials, the HVOF 1350V (WC/Co/Cr) and Arc Spraying 95MXC (amorphous alloy) coating types which gave the best results, were used for further experimentation in varying the speed and the angle. Specimen of 13.4 steel are tested in the same conditions to offer reference values in order to measure the improvement of erosion resistance reached by the best tested materials.

4.2 Influence of speed

Both HVOF and Arc Spraying coatings have been tested for a large range of speed in the following conditions :

Sand concentration	0.3 g/l	0.3 g/l	0.3 g/l	0.3 g/l
Particles size	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Jet speeds	25 m/s	45m/s	65m/s	90m/s
Jet angle against specimen surface	15°	15°	15°	15°

The results are given in the diagram of Fig 5 showing the erosion rate Er [mm^3/h] as a function of the speed v [m/s]. For each of the three materials (HVOF 1350V, Arc Spraying 95MXC and 13.4 steel), the erosion rate follows a power law with the speed:

Material	*A*	*B*
13.4 steel	0.000076	2.84
Arc Spraying 95MXC	0.0000036	3.35
HVOF 1350V	0.000024	2.58

$$Er = A \cdot v^B$$

The value of B coefficient gives an information about the erosion process. It is considered that a B value lower than 3 characterizes a ductile erosion and that a range of B value between 3 and 6 indicates a brittle erosion. [6].

This test shows above all the very high resistance of the HVOF 1350V coating. The loss of volume is measured up to 110 times lower of this of base material 13.4 steel.

The Arc Spraying coating 95MXC represents an improvement of erosion resistance in comparison with the 13.4 steel of only 2.5 to 4.5. Nevertheless, the applicable thickness of this coating can reach 4 mm still being very cost efficient.

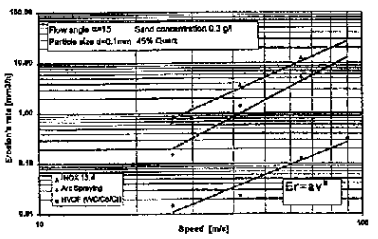

Fig 5 Erosion as function of speed

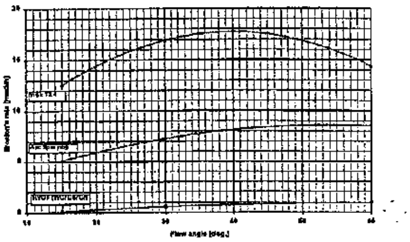

Fig. 6 Influence of flow angle

4.3 Influence of flow angle

In order to qualify those materials for different hydraulic applications, tests with angle variation have also been performed (Fig. 6).

This result shows that the relative improvement in erosion resistance of both HVOF 1350V and Arc Spraying 95 MXC against 13.4 steel reduces for very high angles of flow. All tested materials trend to have a ductile behavior by showing a maximal erosion rate at an angle who seems to be lower than 90 degrees [7]. The ductility of 13.4 steel itself is the highest. This explains why the 13.4 steel keeps a good resistance against erosion with high flow angles. Other tests are going to be performed with angles smaller then 15 degrees.

5. Field application data

5.1 Cavitation

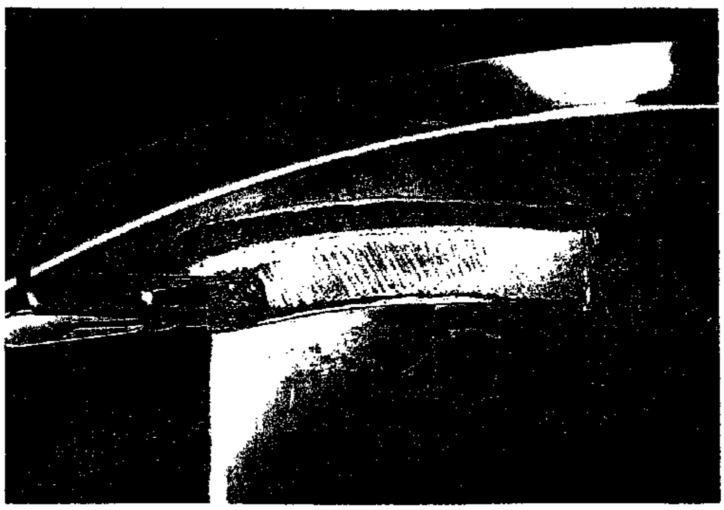

Fig. 7 Pump turbine Isogyre, Malta Oberstufe/ÖDK, Carinthia
60 MW, 35 m³/s, 50 – 200 m, 375/500 1/min welding with Cavitec

Fig. 7 shows the repair of a 60 MW Francis pump turbine which is one of three wheels installed at the Malta Oberstufe in Carinthia/Austria (Österreichische Draukraftwerke /ÖDK). The pumps can cover a height difference of 50 to 200 m and run at a speed of 375 respectively 500 1/min. At the upper limit of the banked up water level severe cavitation occurs at the inlet edges of the pump turbine.

A change in the hydraulic shape could not improve the situation essentially. Therefore a coating was tried on the exposed areas with a 5 mm thick layer of Cavitec. The result is an increase of the repair interval from 3000 to >9000 h today [9].

5.2 Erosion

This case study describes a 6 MW eight steps high pressure pump turbine at the Österreiches Draukraftwerke. The driving water is highly loaded with sand, particles above 0,5 mm are separated, still there is a high load in the water, which results in erosion between the cylindrical gaps of the shaft seals and the runners. The service life is according to changes in water quality, 3000 to 6000 h. In case of sand avanches, for example the wear reservoir might be even destroyed in a few days, the leaking water rises considerably and the pump turbines have to be repaired immediately.
As a preventive measure the rings were coated with a 0,3 mm HVOF 1350V coating. Although the expected friction behaviour (the coefficient of friction for WC/Co/Cr to WC/Co/Cr is about 0,2 in aqueous environment) is positive, the gap width was increased from 0,05 to 0,25 - 0,35 mm for security reasons. Until now the results were positive, the wear after 2200 h is hardly measurable and is not more than 0,025 mm. Thus repairs intervals could be elongated considerably by thermal spraying.

6. Summary
Chrome-Nickel martensitic steels are still approved base metals against cavitation, corrosion and moderate abrasion or erosion. For a longtime, all scientific efforts were focused on these steels and their behaviour in practice.

Some years ago the tendency changed and it was accepted that wear could be relocated in such a way that expensive parts are no longer in direct contact with heavy wear mechanisms. Surface protection is the new wave considerably increasing the life time, availability and mean time of repair or failure.
Surface protection technologies such as HVOF or arc spraying as well as new tailor made materials, e.g. Cavitec, offer the possibility of optimized maintenance solutions.

7) References

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