A REVIEW OF CAVITATION-EROSION RESISTANT WELD SURFACING ALLOYS FOR HYDROTURBINES

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Abstract

An improved weld surfacing alloy has been developed and tested to resist cavitation-erosion in hydroturbines. Typical wear characteristics experienced in laboratory testing has been correlated to actual service conditions. A metallurgical evaluation shows that a high strain, work hardening austenitic stainless steel produces superior resistance to cavitational erosion. Several industrial alloys were evaluated using the vibratory and high velocity cavitation test, to produce a new alloy development in weld surfacing. Field testing shows an improvement in cavitation-erosion resistance of up to 800% relative to 308 stainless steel.

Keywords

Welding, Surfacing, Cavitation, Erosion, Wear, Turbines,

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1. INTRODUCTION

Cavitation occurs to various degrees in all types of fluid handling equipment including propellers, pumps, piping systems and large turbines. Equipment used for the movement of fluids is an important part of most manufacturing industries. Hydro-electricity, coal-fired power utilities, marine, chemical, pulp & paper and petrochemical industries are such examples. With reference to the generation of electrical domestic power, most of the electrical energy requirements are satisfied using traditional coal-fired steam turbines. However this process has energy extraction efficiencies as low as 30% and is a major contributor to pollution. Electrical energy extraction up to 90% is regularly achieved using hydraulic turbines (hydro-turbines). Hydro-stations form a very important part of the overall electricity system for many different countries. In New Zealand, approximately 80% of operational power stations are hydro stations [1].

For efficient operation of a hydro-turbine, it must have specific shape and contour. Cavitation-erosion leaves behind cavities or pits which affect these important contours, creating obstacles to smooth flow of water through the turbine. This leads to a loss of operating efficiency of the turbine. Considering the cost of electrical energy, even a relatively small change in the operating efficiency can be very expensive. Cavitation causes surface penetration damage of up to 10 mm per year to critical components such as impellors, turbine blades, and casings [2]. The end result is a reduction in energy extraction capacity that can lead to losses in terms of downtime, productivity, efficiency and money. Today, hydro-turbines are more powerful and more compact, two factors that can lead to greater risk of cavitation.

The use of cavitation resistant surfacing (both as a preventative measure and to repair cavitation damage) remains one of the best and most economical ways to control cavitation on carbon steel and stainless steel, the predominant base materials used for turbine runners. Selecting a wear surfacing alloy such as austenitic stainless steel has been a traditional solution for many years. With severe cavitational wear, the use of high carbon, cobalt base alloys with relatively high hardness and corrosion resistance as also been used. However cobalt base alloys, as deposited, are more crack sensitive, difficult to grind to contour and are relatively quite expensive.

Extensive research has been carried out with the aim of formulating an economical cobalt containing stainless steel weld surfacing alloy that produces a highly cavitational wear resistant layer. Extensive laboratory and field tests have been conducted with a large number of weld surfacing materials. Depositing a new highly cavitation resistant alloy known as CaviTec(1) by pulsed gas metal arc welding certainly produced the best results from technical as well as commercial points of view.

2. TYPES OF HYDRO-TURBINES

Hydro engineers generally select the type of turbine runner based on the water resource variables that are available due to local conditions. For example, pressure gradient, water velocity, turbulence, local terrain etc, are considered in order to optimise the available energy. Figure 1 shows schematically a sectional view of a hydro-station.

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(1) CaviTec is a tradename of Eutectic+Castolin

Figure 1: Sectional view showing turbine flow parameters [3]

There are several basic configurations of hydro-turbines in use. However the most common is the Francis turbine runner, as shown in Figure 2.

Figure 2: The Francis turbine runner

The Francis turbine operates with a pressure head of between 30 and 60 meters. The Francis turbine runner has a high operating efficiency(approximately 90%) over a wide range of head heights and flow rates. The size of a Francis turbine runner can range from less than one metre to over fifteen metres in diameter. A typical size used in New Zealand hydro-stations would be three metres.

3. CAVITATION -- EROSION IN HYDRO-TURBINES

Also known as “pitting” erosion, cavitation on hydro-turbines occurs as a result of the steady erosion of particles from the turbine surface, as shown in Figure 3. Pitting depth exceeding 40mm in depth has been observed on hydro-turbine runner surfaces. Typical metal losses experienced in the hydro-generating industry can average approximately $5kg/m^2/10{,}000$ hours (generally repair is scheduled at 40,000 hours). For a turbine runner over a period of several years, metal losses up to 200kg is not uncommon [4].

Figure 3: Pitting erosion on Francis turbine blades

As water flows past the material surface at relatively high velocity, turbulence can occur by changes in flow direction, pressure and velocity. As a result of the venturi effect, when water passes through a turbine, its local pressure can drop below the vapour-pressure value. This is shown schematically in Figure 4. At high water flow velocities, vapour bubbles or cavities appear in the water and grow very rapidly (from approximately 10^6/sec and from 0.1mm in size). Because of subsequent changes in water velocity or pressure, these cavities are forced to implode (ie. collapse) violently in a few microseconds.

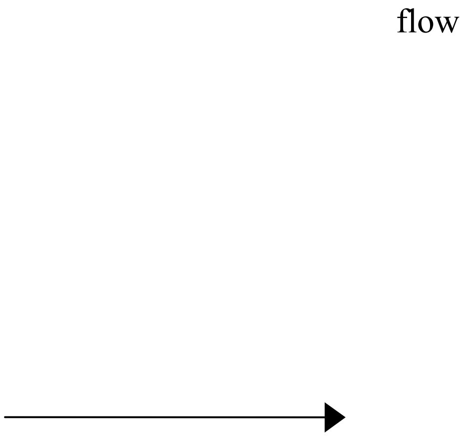

Figure 4: Pressure profile across blade leading to cavitation [5]

This produces shock waves on the turbine runner surface which can approach 1500MPa, exceeding the yield strength of most materials, and producing permanent deformation. While water flows through the turbine, such repetitive formation and collapse of cavities generates shock waves at a regular frequency, which subject the neighbouring surface material to a combination of impact and low-cycle fatigue stresses. Depending on its properties, the surface material undergoes elastic and plastic deformation and after some time, develops a network of small cracks. When the cracks join, small particles break loose, leaving behind a pitted surface as shown in Figure 3. Cavitation-erosion can continue as long as water flows through the turbine.

Up to 90% of hydro-turbines suffer cavitation damage to some extent [4]. As already noted, cavitation-erosion is most likely to occur on the low pressure side of the turbine runner blades. Figure 5 shows schematically the general location of wear areas caused by cavitation-erosion in a Francis turbine.

Figure 5: General location of typical cavitation damage in Francis turbines [4]

When cavitation damaged, weld surfacing is, in many cases, the key solution.

4. CAVITATION TEST METHODS AND RESULTS

There are several laboratory and small scale test models that have been developed for evaluating cavitation resistance. For more than 15 years, two tests have been used specifically for studying cavitation-erosion in hydro-turbines:

- ASTM G32 Vibratory Cavitation Test (introduced 1972)
- TVA(2) High Velocity Jet Cavitation Test

Both are simple, rapid, and economical. These two tests have been used extensively to rank the cavitation-erosion resistance of over 200 industrial alloys. The results have shown that the development of cavitation erosion generally goes through a number of periods as shown in Figure 6.

The initial period where no weight loss occurs is known as the ***incubation period***. As measured in these laboratory tests, it is in the order of a few hours for the harder stainless steels and cobalt base alloys. Then follows a steady rate of weight loss. If the test is prolonged, the rate of weight loss decreases due to surface roughness.

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(2) Tennessee Valley Authority

Figure 6: Typical cavitation erosion curve [6]

The weight loss curves for several alloys obtained in the vibratory test is shown in Figure 7.

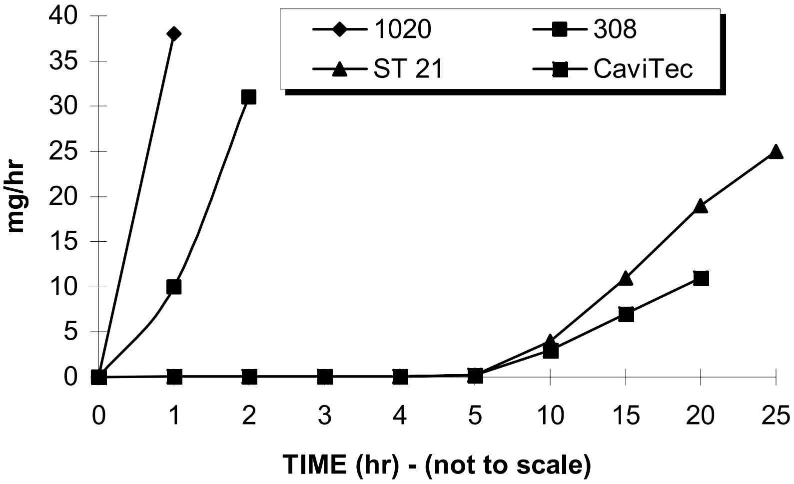

Figure 7: Cumulative weight loss of various industrial alloys

measured using ASTM G32 test [7]

It is the maximum or ***steady-state wear rate*** that is used to rank the cavitation resistance. Figure 8 presents the ranking thus obtained for several alloys.

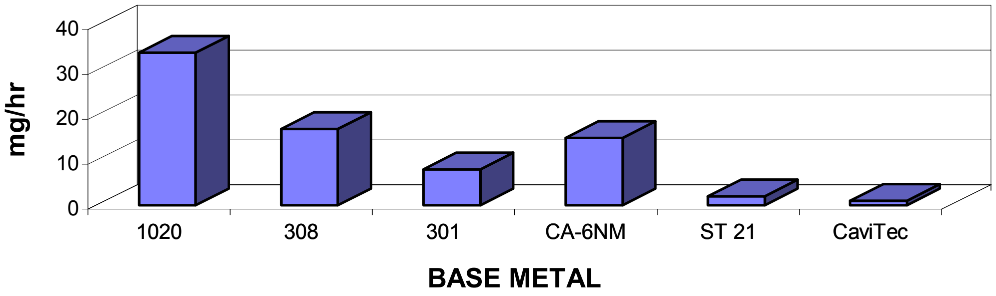

Figure 8: Steady state erosion rate of various alloys [7]

The high velocity cavitation jet test produces very high intensity cavitation and can erode industrial materials in a much shorter time (of the order of ten times) compared to the vibration cavitation test. To assess the relative cavitation-resistance of several base metals and weld surfaces, the inverse of the steady rate weight loss has been plotted in Figure 9, using data extrapolated from both test methods [7,8].

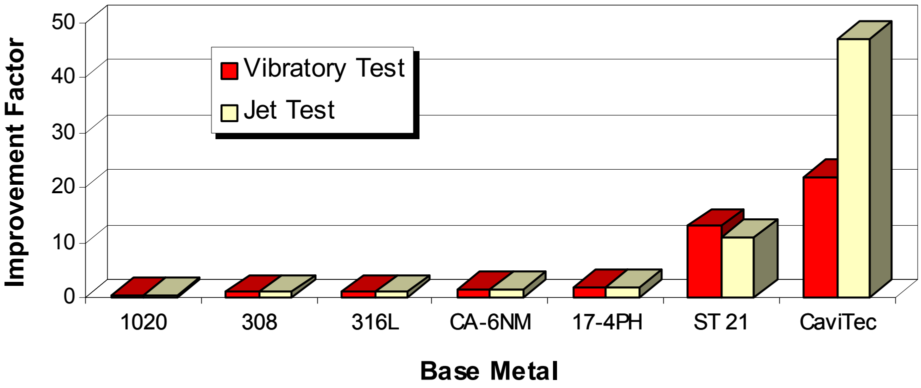

Figure 9: Cavitation improvement of various metals relative to 308 stainless steel [8]

Similar results are obtained between the two tests, however some discrepancy can be seen for the more highly cavitation resistant materials. CaviTec shows a cavitation resistance improvement factor relative to 308 stainless steel of between 20 and 50 depending on which test is used. It has been recently proposed that the differences may be the result of the cavitation impact intensity which is of the order of 10 times higher in the jet test. It has been observed that the vibratory test produces a high number (high density and frequency) of repeated impacts but at a relatively low intensity producing mainly fatigue elastic deformation. The high velocity flow jet test produces a much smaller number of repeated impacts but at a higher intensity producing more plastic deformation and surface hardening. Because CaviTec has been developed to surface harden and extend the incubation period by eroding at a much slower rate, a higher improvement factor is shown.

4.1 EFFECT OF HARDNESS

Figure 10 illustrates the steady state erosion rate plotted as a function of surface hardness. There is, as expected, some correlation between cavitation rate and weld surface hardness. However, there is also some deviation from the correlation for the more tougher weld alloys below the curve. In this group are the low nickel and manganese stainless steels and cobalt base alloys. This is due to the high strain hardening properties of these alloys[9]. This group of alloys are not too hard and can be ground easily to a desired blade contour (an essential requirement of the surfacing material).

The results show that cavitation induced surface hardening would assist in minimising cavitational wear.

Figure 10: Cavitation wear rate as a function of weld deposit hardness

relative to 308 stainless steel [8]

4.2 EFFECT OF STRAIN HARDENING

The importance of martensitic transformation occurring at the material surface in promoting strain hardening and resistance to cavitation is illustrated in Figure 11. Alloys that possess relatively low yield strength and fine deformation (twinning) mechanisms allow good deformation energy absorption when subject to cavitational stresses. Manganese bearing stainless steels and cobalt base alloys are good examples. In addition, the importance of planar slip mode associated with a low stacking fault energy contributing to fine particle removal under cavitational wear has also been demonstrated [9-11].

Figure 11 shows the amount of deformation induced martensite formed for several low stacking fault energy (SFE) stainless steels. Alloys with low SFE and high strain hardening show improved cavitation resistance. The higher the cavitation wear resistance, the less the plastic deformation required to transform the FCC austenitic phase to the BCC martensitic phase. Figure 11 indicates that there is almost no trace of austenite phase on the surface of CaviTec after exposure to cavitation.

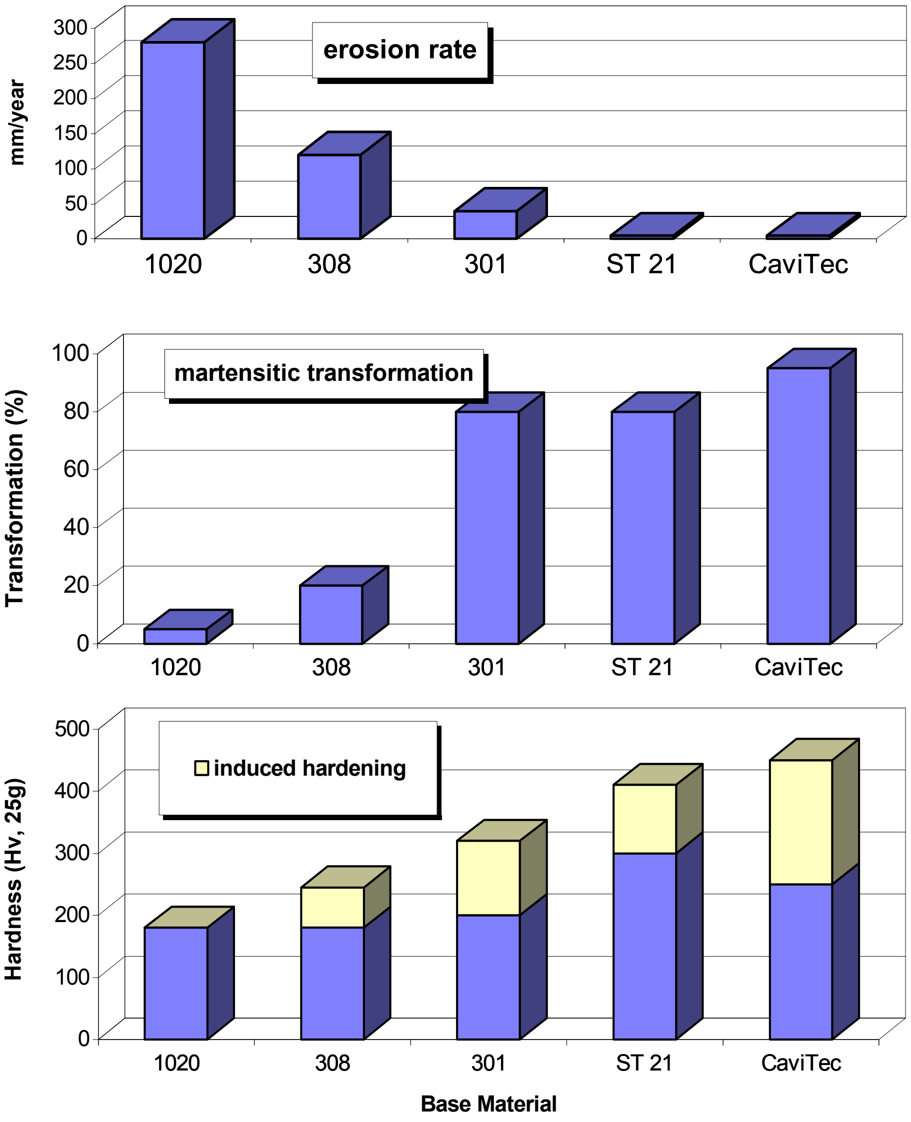

Figure 11: Comparison of cavitation erosion rate with induced phase transformation and hardening [10].

4.3 EFFECT OF ALLOYING ELEMENTS

The results obtained by laboratory testing has shown that the low nickel and manganese bearing austenitic stainless steels present the best cavitation resistance amongst the conventional stainless steels. These steels have a metastable austenitic phase and are known to have high strain hardening and strain induced martensitic transformation.

The excellent cavitation resistance of cobalt base alloys has been well known since the early seventies [12]. It has been proposed that the key microstructural factor for these alloys is the fine deformation twinning accompanying the cavitation induced phase transformation in low SFE alloys.

The planar slip mode and the high strain hardening of low SFE materials delays the development of localised stresses required to initiate fracture thus increasing surface hardness, fatigue strength and consequently cavitation resistance. In addition, the continuous fine twinning leads to the production of very small eroded metallic particles, thus decreasing the weight loss rate.

Understanding the fundamental causes of the cavitation resistance of cobalt alloys suggested that it might be possible to reproduce a more economical iron-base alloy with similar low SFE and deformation hardening and refining, leading to similar outstanding cavitational resistance [2].

Various concentrations of nine elements, as shown in Table 1, were evaluated. In addition to cavitation wear testing, metallography, scanning electron microscopy, x-ray diffraction, hardness, ferrogauge and bending tests were also used.

Table 1

Range of concentrations tested.

C	**Mn**	**Si**	**Cr**	**Ni**	**Cu**	**N**	**Mo**	**B**	**Fe**
0.02	0	0	5	0	0	0.02	0	0	Bal
1.1	17	5	20	10	60	0.35	6	0.2	Bal

The influence of individual elements on cavitation erosion rate was evaluated using multiple linear regression techniques to assist in refining the final alloy composition. The results showed that optimising the cavitation resistance can be induced by the following property changes:

(1) martensitic transformation - by promoting resistance to low cycle fatigue mechanisms observed in the vibratory cavitation test

(2) surface work hardening - by prompting strain hardening.

(3) planar slip (low SFE) which leads to fine particle removal

To illustrate the effect of alloy chemistry on improving cavitation resistance, some examples follow.

For example, carbon and nitrogen combined was found to benefit cavitational resistance. Nitrogen is also known to improve the fatigue resistance of austenitic stainless steels. Figure 12 shows the combined effect of carbon and nitrogen content on the steady state wear rate as measured in the vibratory cavitation test.

Figure 12: Effect of $C+N_2$ on cavitation resistance of CaviTec alloy [11]

Figure 13 illustrates the effect of cobalt concentration on the erosion rate of CaviTec alloy

Figure 13: Effect of cobalt on cavitation wear resistance of CaviTec [11]

Nickel and carbon additions were found to increase the SFE while Cr, Si, Mn, Co and N additions produced a decrease in SFE in austenitic stainless steels [13]. Decreasing the nickel content and substituting with cobalt resulted in a decrease in yield strength, but more importantly, produced an increase in ultimate tensile strength.

These findings prompted the replacement of nickel with manganese and nitrogen in order to promote the formation of martensite and planar deformation. Chromium and cobalt also ensured good corrosion resistance.

These results provided preliminary compositions for a new weld surfacing alloy. Weldability and ductility tests were then evaluated to further refine the final composition.

The patented composition is shown in Table 2.

Table 2

Chemical analysis of CaviTec (%wt)

C	Mn	Si	Cr	Co	N
0.2	10	3	17	9	0.2

5. PROPERTIES OF CAVITEC ALLOY

The results obtained have shown that many material properties are required to provide good cavitational resistance. The surfacing alloy must possess resilience, hardness, toughness, fatigue strength, strain hardening, and corrosion resistance. Weldability and grindability are also important considerations from an application point of view.

CaviTec has outstanding cavitation erosion resistance, similar to some cobalt base alloy grades. With only 9% cobalt, it is an iron base alloy more economical to use than cobalt base alloy grades. Its formulation has been designed to yield the highest work hardening and lowest stacking fault energy, with high interstitial carbon and nitrogen content.

CaviTec has the following mechanical properties (as welded):

Ultimate Tensile Strength : 860MPa
Yield Strength : 610MPa
Elongation (50mm) : 12%
Hardness : 25Rc

The high tensile strength of CaviTec is related to its high strain hardening coefficient. It offers good ductility and easy grind finishing due to its low (as welded) hardness. In order to achieve these goals, a compromise had to be made between cavitation resistance, ductility (weldability) by keeping the carbon content below 0.2%.

The patented composition of CaviTec provides a metastable austenitic microstructure in the as-welded condition. Under cavitational stresses, the austenitic phase transforms to martensite, deforming by twinning. Such phase transformation and fine twinning absorb the energy of shock waves generated by the collapsing vapour cavities in water (ie, cavitation stresses). As a simplification, we can consider that under cavitational stresses, CaviTec undergoes surface hardening up to 450Hv (as shown in Figure 11). The metal loss in the incubation period stays generally at a minimum and the surface remains smooth and hardened. The incubation period for CaviTec is thus much longer than for common stainless steels such as 308 grade. CaviTec can therefore sustain cavitation stresses without any erosion damage occurring for a much longer period of time.

After full hardening has occurred, further exposure to cavitational stresses eventually causes fatigue cracking on the surface. As discussed previously, this leads to subsequent detachment of particles at the intersection of the deformation twins. Since the twins are relatively small, only small metal particles detach and as a result, the cavitation damage is still relatively slow [11].

6. FIELD RESULTS

Field tests have been carried out mainly in Canada to verify the laboratory results. The incubation period measured in the field can be significant, up to 1 year in some circumstances. The field results shown in Figure 14 indicate that the cavitation resistance of CaviTec is about 4 to 10 times that of stainless steel 308, conventionally used for cavitation repairs.

The differences between laboratory and field results may be due to cavitational impact intensities as discussed earlier. Other factors that have been proposed are inaccurate inspection data, too thin weld overlays, weld dilution and varying local conditions(head height etc).

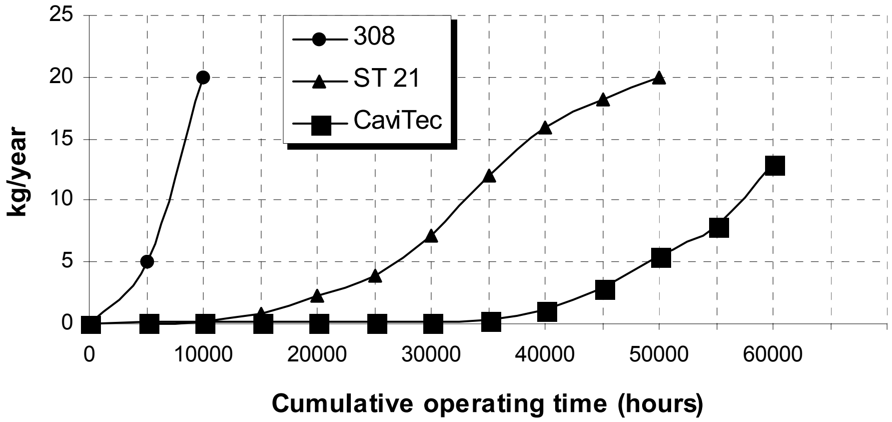

Figure 14: Model regression curves showing metal loss for 3 weld alloys

on a Francis turbine [6]

Hydro-power stations are now able to reduce their cavitation repair frequency to approximately one third by using CaviTec instead of 308 stainless steel.

The use of CaviTec has been estimated to lead to an economic benefit (additional energy gain and reduced repair costs) of about \$2.5 million per year for one Canadian hydro-electricity utility [14].

7. CONCLUSIONS

The use of laboratory testing has provided consistent and reproducible results. The relative cavitation erosion rate, referenced to a commonly used repair material such as conventional austenitic stainless steel provides a good method for ranking various surface materials. The findings have led to the development of a new highly resistant austenitic stainless steel now known as CaviTec. The chemistry of the weld overlay has been formulated to reproduce in an economical iron-base matrix, the same type of fine planar deformation and strain hardening associated with low SFE, as observed in cobalt base alloys. Surface hardening and martensitic transformation by cavitation impacts are key factors in regenerating continuously under cavitation exposure, an efficient surface barrier against cavitation erosive attack.

Field test results are consistent with the laboratory findings, albeit on a much slower scale.

CaviTec weld surfacing has demonstrated excellent cavitation erosion resistance.

The increasing cost of energy and cavitation damage to turbines, together with the availability of higher resistant alloys have led to a drastic decrease of allowable cavitation metal loss as specified by OEM(3) contractual guarantees. Metal loss guarantees as low as 2kg and erosion depths as small as 3mm per 10,000 operating hours are now commonly specified. OEM's are now allowed to use cavitation resistant weld surfacing alloys such as CaviTec as weld protective overlays on new turbine runners.

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