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Improving cavitation erosion resistance of austenitic stainless steel in liquid sodium by hardfacing – comparison of Ni and Co based deposits

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ABSTRACT

Cavitation affects the performance of hydraulic machinery and also results in erosion damage. Although the damage produced in sodium is more intense than that in water, it is uneconomical to design hydraulics to totally avoid cavitation. The designer is left with the choices of improving hydraulic design and/or using materials/coatings with good resistance to cavitation. Susceptibility to cavitation is evaluated for two different hardfaced coatings, viz. Co-based Stellite6® alloy coatings and Ni-based Colmonoy5® coatings, and the results compared with that for 316L austenitic stainless steel. Study reveals that Stellite6 alloy coating is more resistant to cavitation than Colmonoy5 in liquid sodium. However, the cavitation resistance of Colmonoy5 coating is better than that of austenitic stainless steel 316L, the substrate material on which these alloys are deposited. Results are explained based on the differences in the stacking fault energy and fracture toughness of the materials.

1. Introduction

Cavitation occurs in a hydraulic system when the static pressure at any point in the flow field drops below the vapor pressure of the liquid at the operating temperature. The resulting vapor cavities are transported by the flowing liquid and collapse when the pressure recovers producing extremely high localized pressure and temperature spikes [1–4]. Collapse of these cavities adjacent to metal boundaries causes severe pitting of the metal surface and thus affects the life of the equipment. Cavitation can be prevented by improved hydraulic design of plant and equipment resulting in increased available energy and reduced equipment requirement. It can also be prevented through the use of materials and coatings with high resistance to cavitation thus permitting operation with some degree of cavitation. This is often necessary because a cavitation free environment is often economically unrealizable.

1.1. *Mechanism of cavitation damage*

Rayleigh [5] in his seminal paper proposed the idea of material damage due to shock waves resulting from the symmetrical collapse of individual empty or vapor filled spherical bubbles, at constant pressure during the collapse process, in an inviscid, incompressible liquid. This work was extended by Plesset, Poritsky and others to include the effects of internal pressure of gas in the bubble and the effects of liquid properties like surface tension and viscosity to give the now famous Rayleigh–Plesset equation for the collapse pressure of a single bubble. An alternative damage mechanism that has been proposed in cases where extremely high shock waves are not plausible is that due to microjets [1,6], of diameter ranging from few microns to several hundred microns, which are expected to occur when collapsing bubbles are distorted by pressure gradients or when they are located adjacent to solid boundaries resulting in the movement of high velocity liquid microjets through the cavity. The damaging phenomenon is thus characterized by high pressures and temperatures existing in localized regions (of few microns to hundreds of microns) over very short periods of the order of microseconds. In reality, the resulting shock wave or micro jet is due to the collapse of a cluster of bubbles/cavities with the collapsing cavities in the periphery serving to reinforce those at the center [7]. The surface is therefore subjected to repeated mechanical loading at high frequency. If the stresses generated are higher than the elastic limit this can result in permanent deformation; however, if the stresses are less than the elastic limit then failure can occur by fatigue. The capacity of the material to absorb the energy from bubble collapse without

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damage is a measure of the cavitation erosion resistance of the material.

1.2. Cavitation erosion in fast reactor

Fast reactors employ centrifugal sodium pumps for circulation of liquid sodium coolant in the primary and secondary heat transport circuits. These pumps work in a modest Net Positive Suction Head (NPSH) environment resulting from the need to maintain low cover gas pressure (to ensure easy and effective sealing of radioactive cover gas) and minimum submergence (to reduce span of the rotating assembly and achieve required margin between critical speed and operating speed). The operating NPSH margin (NPSHA/NPSHR where NPSHA is the available plant NPSH and NPSHR is the required NPSH of the impeller) does not totally preclude the occurrence of cavitation although it ensures that there is no head drop due to cavitation. By permitting the pumps to operate at NPSH values below that corresponding to inception of cavitation bubbles, the pumps can be made compact thereby reducing capital cost. However, the degree of cavitation allowed is such as to ensure sustained and maintenance free operation over long periods.

The component of a pump most susceptible to cavitation is the impeller and damage due to cavitation can occur in both the suction side of the blade (classical cavitation) as well as the discharge side of the blade (recirculatory cavitation). The impeller can be designed to resist cavitation by (a) proper material selection (b) optimizing the hydraulic design of the impeller to delay cavitation inception, and (c) by using protective coating or surface treatment of material to increase resistance to cavitation erosion. The material of construction of both primary and secondary sodium pump impellers in a fast reactor is CF3 (austenitic stainless steel casting equivalent to wrought material 304L).

Model testing can be used to validate the design and identify cavitation susceptible areas in the pump impeller. Hardfacing/surface treatment of these regions in the prototype can be used to improve the resistance to cavitation erosion and increase pump life.

1.3. Hard facing and surface treatment methods to improve cavitation resistance

A study of cavitation erosion literature reveals that several hardfacing/surface treatment techniques are being studied to improve resistance to cavitation erosion. These include hardfacing (using Stellite [8], Colmonoy [9]), hard chrome plating [10], metal plating [11], coatings (nanocrystalline TiN [12], Cr–N [13], etc.), surface treatment methods [14,15] and laser surface modification [16]. In fast reactors, Colmonoy and Stellite are commonly used for hard facing components.

Stellite6 is a cobalt based alloy with 27%Cr, 2.5%Ni, 0.08%W and 1%C. Its microstructure consisting of Co phase dendrites with interdendrite lamella of Cr rich carbides provides the alloy with the hardness to resist cavitation damage. On irradiation in the reactor, the stable isotope Co^{59} is transmuted to radioactive Co^{60}. The isotope Co^{60} emits γ radiation of 1.17 MeV and 1.33 MeV energy with a half life of 5.3 years. It therefore poses problems during maintenance and repair of hardfaced components.

Colmonoy5 is a Nickel based alloy with 11.5% Cr, 3.75% Si, 2.5% Boron and 0.65% Carbon. It contains high volume fraction of interdendrite carbides, borides, silicides along with eutectic lamella of borides/silicides/Ni phase and relatively soft Ni/phase dendrites. The hard interdendrite phases provide it with high resistance to wear. It does not become active under irradiation and is therefore preferred for hardfacing nuclear reactor components especially those that require regular maintenance.

Accordingly, in the Indian Prototype Fast Breeder Reactor (PFBR), Colmonoy is the material of choice for hardfacing various reactor components [17].

Components hard faced with Colmonoy5, in the centrifugal coolant pumps of PFBR, include the hydrostatic bearing (for both primary and secondary pumps), the pump pipe connection (in the primary pump) and the piston ring seals (in the secondary pump). The main hydraulic components, viz. suction casing, impeller and diffuser, which are made of CF3, are not hard faced. Hard facing/surface treatment/surface modification of components such as pump impeller is challenging because of the complex vane profile and the danger of distortion during the process resulting in changes in the blade profile/vane angles. Boy et al. [19] and Sollars [20] discuss the application of thermal spray coating to bolster resistance to cavitation erosion in water turbines and pumps. Application of hard facing/surface treatment techniques on cavitation susceptible regions of pump hydraulics of future FBR's deserves consideration especially in view of the modest available NPSH and high suction specific speed design for pumps of future FBR's.

Most of the laboratory work done on cavitation erosion resistance of stainless steel and hardfaced materials has been in water. Work done in sodium, in the 1960's and 1970''s in USA and France, has mainly involved stainless steels (316, 316L, and 3121), iron base alloys (Sicromo 9M, A-286), nickel base alloys (Inconel 600, Hastelloy X, Rene 41), cobalt base alloys (L-605, Stellite6B) and refractory alloys [21–24]. However, little published literature [9] exists on the cavitation damage resistance of Colmonoy in liquid sodium. As Colmonoy5 is the hardfacing material for components in PFBR, it is important to study the improvement in cavitation damage resistance achieved by hard facing as well as to study the relative cavitation damage resistance of Colmonoy5 vis-à-vis Stellite6.

1.4. Parameters affecting cavitation erosion and need for testing in sodium

Erosion due to cavitation is a complex phenomenon dependent on both liquid and material properties. The important liquid properties that influence the magnitude of the collapse pressure of the vapor bubbles are vapor pressure, bulk modulus, density, surface tension, dissolved gas content and to a lesser extent viscosity, while the material properties that govern resistance to cavitation damage are yield strength, ultimate tensile strength, hardness, strain energy, resilience etc. [25,26]. The vapor pressure of sodium at the reactor cold pool temperature of ~400 °C is very small (~27 Pa) compared to that of water at room temperature (4905 Pa). Moreover, the solubility of argon cover gas in sodium is very small compared to that of air in water (eg. the solubility of air in water at 25 °C and atmospheric pressure is 23 wppm [27] while that of argon in sodium at ~400 °C and 1 atm is only 1.54×10^{-3} wppm [28]).

The higher the vapor pressure and the dissolved gas in the liquid, the greater is the back pressure retarding bubble collapse and lower the impact pressure on the surface. Damage is also affected by the acoustic impedance ratio between the liquid and the solid surface and the greater this ratio, the higher the damage produced. The acoustic impedance ratio, $AI = (\rho^{*}C)_{liquid}/(\rho^{*}C)_{solid}$ where ρ=density and C=velocity of sound, in sodium, at the reactor cold pool temperature of 397 °C, is ~1.5 times that in water, at room temperature. The damage due to cavitation in sodium at the reactor cold pool temperature, is therefore, more severe than that produced in water at room temperature.

Hence it is advisable to determine the cavitation erosion resistance of candidate materials directly in sodium instead of measuring it in water and extrapolating the results to sodium.