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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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# 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

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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<sup>®</sup> alloy coatings and Ni-based Colmonoy5<sup>®</sup> 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.

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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







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  $\gamma$  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  $1.54 \times 10^{-3}$  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  $\rho$ =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.

# 2. Description of test facility

The cavitation erosion test facility (Fig. 1) consists of cavitation vessel, dump tank, vibratory cavitation equipment and cover gas system. The vibratory cavitation equipment (Roop Telsonic Ultrasonix, series SG 22) employs a piezoelectric transducer to generate the high frequency vibratory motion. The facility is designed to be in conformance with ASTM G 32 which outlines the requirements to be met (such as dimensions of vessel, immersion depth, dimensions of specimen, equipment operating parameters and their control) for cavitation erosion testing using the vibratory method. The facility and the detailed test procedure are described elsewhere [29].

#### 2.1. Details of test specimens

Fig. 2 shows a typical test specimen. Three types of specimens were tested. Type 1 was austenitic stainless steel (SS 316L) machined from bar stock, Type 2 was austenitic stainless steel (SS 316L) machined from bar stock and hard faced with Colmonoy5 and Type 3 was austenitic stainless steel (SS 316L) machined from bar stock and hard faced with Stellite6. The tests were done in sodium at temperatures of 200 °C, 250 °C and 300 °C. At 200 °C, three nos. of SS 316L specimens, two nos. each of Colmonoy5 hardfaced specimens and Stellite6 hardfaced specimens were tested; at 250 °C, two nos. of SS 316L specimens, three nos. of SC 316L specimens, three nos. of SS 316L specimens, three nos. of SC 316L specimens, three nos. of SC 316L specimens, three nos. of SC 316L specimens, two nos. of SC 316L specimens, three nos. of SC 316L specimens, two nos. of SC 316L specimens, three nos. of SC 316L specimens, two nos. of SC 316L spe

Some properties of the deposits are given in Table 1:

## 2.2. Sodium purity

The impurity levels present in the initial charge of sodium are: O=3.4 ppm, C=25 ppm, Ca=1 ppm, Mg=0.25 ppm, Co<1 ppm, Cr<1 ppm, Cu<1 ppm, Fe=7 ppm, Mn<1 ppm, and Ni=1.2 ppm.

The system does not have a built in purification facility. Although care was taken through operational procedures to



Fig. 1. Cavitation erosion test facility.



Fig. 2. Cavitation Specimen.

Table 1Properties of hard faced deposits.

Properties	SS 316L	Hardfacing		
		Stellite 6	Colmonoy5	
Deposit thickness, mm (average)	-	$\sim$ 1.5	$\sim$ 1.5	
Density, gm/cm <sup>3</sup> Hardness, Maximum value Mean+SD (measured from 2 random samples in each type using FIE, model RASNE- 1 digital Rockwell hardness tester)	7.99 96.4 HRB 95.5 ± 0.6 HRB (233 VHN)	8.12 <b>[30]</b> 39.4 HRC 38.5 ± 0.8 (369 VHN)	8.14 [31] 44.4 HRC 40.9 ± 3.2 (393 VHN)	

The chemical composition of the base metal of the specimens (SS 316L) specimens tested is shown in Table 2 (by direct reading spark optical emission spectrometer).

maintain inert atmosphere in the facility, it was observed after several experiments ( $\sim$ 50 nos.) that the impurity level in the system had increased. It is reported [22,24] that oxygen level of 100 ppm in sodium does not have adverse effect on resistance to cavitation erosion in stainless steel. In this case the maximum expected oxygen impurity at the highest temperature (300 °C), at which the experiments were done, assuming saturation conditions, is 100 ppm.

# 2.3. Operating parameters

The following are the operating parameters:

Frequency of operation: 20 kHz, amplitude of operation (peak to peak): 25  $\mu$ , power of ultrasonic generator: 3000 W, submergence of specimen=8 mm (min) to 13 mm (max), pressure of argon cover gas in cavitation vessel=100 mbar(g).

# 2.4. Experimental Procedure

The specimen is polished, cleaned using water and then with acetone, dried and weighed using an electronic balance of 0.1 mg accuracy. In the case of specimens which are to be examined by SEM during the course of the testing, the specimens are also examined before start of tests by SEM. The specimen is assembled

Table 2Chemical composition of SS 316L.

Element	Cr	Ni	С	Mn	Мо	Si	Cu	Со	W	Va	Ti	Al
wt%	$17.5\pm0.6$	$10\pm0.3$	$0.02\pm0.002$	$1.63\pm0.07$	$2.05\pm0.02$	$0.38 \! + \! 0.02$	$\textbf{0.34} \pm \textbf{0.02}$	$0.11 \pm 0.01$	$\textbf{0.08} \pm \textbf{0.01}$	$\textbf{0.07} \pm \textbf{0.01}$	< 0.08	< 0.03

 Table 3

 Typical compositions of Colmonoy5 and Stellite6 [17].

wt%									
Alloy Stellite 6	B - 25	C 1.0	Cr 27.0	Co 60	Fe < 2.5	Mn 1.0	Ni < 2.5	Si 1.0	$\begin{array}{c} W \\ \textbf{0.08} \pm \textbf{0.01} \end{array}$

Typical compositions of the hard facing deposits, Colmonoy5 and Stellite6, are given in Table 3. Both materials were deposited in powder form by Plasma Transfer Arc Welding (PTAW) process [18].

on the ultrasonic horn and the assembly mounted on the vibratory cavitation equipment.

Before starting the experiment, the system is checked for leak tightness by pressure hold test. This is followed by cold purging of the entire system to expel any residual moisture. The system is then preheated and the cavitation vessel purged with argon in hot condition. The ultrasonic horn containing the test specimen is then introduced into the cavitation test vessel with continuous argon purging to prevent air ingress. The cavitation test vessel is then filled with sodium to the required level by pressurizing the dump tank and venting the cavitation test vessel. The level of sodium in the cavitation test vessel is monitored using two nos. of resistance type level probes.

After filling, the cavitation test vessel is isolated from the dump tank. The temperature of sodium in the cavitation test vessel is then stabilized to the test temperature after which the ultrasonic horn is powered to start the experiment. The duration of a single test varies from as low as 5 min (in cases where SEM examination is planned) to as long as 2 h.

After the prescribed test period, the ultrasonic horn is switched off, sodium dumped and the cavitation test vessel cooled to room temperature. The horn is then removed from the vessel under continuous argon purging and sealed in polythene bag in argon atmosphere. The central opening of the cavitation test vessel is closed and both the cavitation test vessel and the dump tank are maintained under inert atmosphere when the system is not in use so as to prevent any air ingress into the system.

The specimen is then removed from the ultrasonic horn, cleaned first with methyl alcohol and then in ultrasonic bath with distilled water before weighing and examination. Care is taken to ensure that the cleaning process does not result in any erosion of the specimen by locating the specimen away from the base of the bath where the transducers are fixed and by suspending the specimen such that its face is away from the transducers in the bath. The specimen is then weighed and also examined using SEM, if required, before it is readied for the next test.

At the end of a test, the cumulative weight loss is the total loss in weight incurred in the particular test and all previous tests. Similarly the cumulative time is the total time duration of all previous tests and the particular test.

If  $W_0$  is the initial weight of the cavitation free specimen specimen,  $W_i$  the weight after the ith test and  $t_i$  the time duration of the ith test, the cumulative weight loss is given by  $\Delta W = W_0 - W_i$ and the cumulative time is  $\Sigma t_i$ . The cumulative weight loss rate,  $\Delta W' = \Delta W / \Sigma t_i$ ,



Fig. 3. SS 316L (surface finish 0.3 µm).



Fig. 4. SEM image – Colmonoy sample (surface finish 2.8  $\mu m)$  in polished condition. The carbides and borides are visible in the better polished bottom region.



Fig. 5. SEM image – Stellite sample (S2) (surface finish  $0.4\,\mu\text{m})$  in polished condition.

# 3. Results

Fig. 3 is the SEM image (taken using Obducat Camscan-3200 SEM) of the polished SS 316L specimen. The specimen is polished to surface finish of 0.3  $\mu$ m and the measured hardness is 95.9 HRB (Table 1). Fig. 4 is the SEM image of Colmonoy5 specimen polished to 2.8  $\mu$ m. The deposit thickness is ~1.5 mm and the measured



Comparison of weight loss in sodium at different temperatures SS 316L and hardfaced (Colmonoy5, Stellite6) materials

Fig. 6. Effect of hardfacing on weight loss due to cavitation damage.



Fig. 7. Effect of hardfacing on weight loss rate due to cavitation damage.

maximum hardness is 41.7 HRC. The borides and carbides in the hard facing are visible on the surface without any etching. Fig. 5 shows the Stellite6 specimen with deposit thickness of ~1.5 mm, surface hardness of 39.4 HRC and polished to 0.4  $\mu$ m. In this case also the carbide network present in the hardfaced coating is revealed clearly without any etching.

The variation of the measured cumulative weight loss (gm) with time and the cumulative weight loss rate (gm/h) with time for the above specimens at the various test temperatures are shown in Figs. 6 and 7 respectively. It is evident from both figures that hard facing results in marked improvement in the cavitation damage resistance of SS 316L. It is also apparent that Stellite6 is more resistant to cavitation than Colmonoy5. The SEM images of the specimens taken at different instants during the test provide additional evidence in support of this.

Figs. 8 and 9 are SEM images of SS 316L specimen early on during the testing and after prolonged exposure to cavitation.

It is seen from Fig. 8 (after test interval of 5 min 2 s) that in SS 316L the accumulation of slip bands results in initiation of micro cracks (A). Plastic deformation then results in enlargement of the micro cracks and void formation. The adjacent voids coalesce leading to material removal (B). The resulting surface has the



Fig. 8. SEM sample of SS 316L – after cavitation in sodium (period=5 min 2 s, Temp=200  $^{\circ}$ C).



Fig. 9. SEM sample of SS 316L – after cavitation in sodium (period=141 min, Temp=200  $^{\circ}$ C).

dimpled topography characteristic of damage in ductile materials. Fig. 9 shows the damage after prolonged exposure. It is seen that at this stage there is also material removal from the work hardened surface to produce gross pitting of the surface

Figs. 10 and 11 show the SEM images of Colmonoy5 hardfaced sample during the test period. Fig. 10(a and b) are the SEM images at an early stage of weight loss after  $\sim 6$  min of testing. It may be seen that damage is initiated at the interface between the hard second phase (borides or carbides) and the matrix. Fig. 10 (b) shows the damage at the interlamellar spacing of the eutectic mixture of matrix and hard second phase. It is observed that extended exposure to cavitation causes the removal of the hard second phase particles from the matrix and the formation of pits as shown in Fig. 11. Also evident is severe deformation of the base matrix. The severity of damage, however, is not as large as it is for SS 316L.

Figs. 12 and 13 are SEM images of the stellited specimen in the course of testing. The SEM image (Fig. 12) during the early stage,  $\sim$ 7 min of exposure, shows that damage is initiated at the interface between the matrix and hard carbide locations. On continued exposure to cavitation, the carbide particles are dislodged resulting in voids at these locations. After prolonged testing, it is observed (Fig. 13) that cracks are initiated in the work hardened matrix resulting in material removal and measurable weight loss.

#### 4. Discussion

The marked reduction in the weight loss produced in the hard faced specimens compared to that produced in SS 316L may be



**Fig. 10.** (a)-Colmonoy sample (C3) – after cavitation in sodium (period = 6 min 6 s, Temp=250 °C). Dendrite phases and initiation of material removal at interdendritic regions. (b)-Colmonoy sample (C3) – after cavitation in sodium (period=6 min 6 s, Temp=250 °C). Flower like dendrite phases; material removal begins at hard interdendritic regions.



**Fig. 11.** Colmonoy sample (C3) – after cavitation in sodium (period=41 min, Temp=250 °C). The voids are regions where the borides and carbides and portions of the base matrix are removed.



**Fig. 12.** Stellite sample (S2) – after cavitation in sodium (period= $7 \min 31$  s, Temp= $250 \degree$ C). Cracks at carbide locations resulting in increased stress concentration and removal of carbide particles from these locations.

attributed to the large variation in hardness between SS316L (HRB 95.9) and the hardfaced variants, viz.HRC 39.4 for Stellite6 and HRC 41.7 for Colmonoy5.

Hardness, however, is not the only property that affects resistance to cavitation damage. A comparison of the damage produced in Stellite6 and Colmonoy5 specimens show that although the measured hardness of Colmonoy5 is higher than that of Stellite6, the damage produced in Colmonoy5 is greater than that produced in Stellite6. This difference may be explained in terms of (i) the



**Fig. 13.** Stellite sample (S2) – after cavitation in sodium (period=42 min, Temp=250  $^{\circ}$ C). Further exposure results in damage propagation to the work hardened matrix.

#### Table 4

Fracture toughness coefficients of Stellite6 and Colmonoy5.

Stellite6	35.6 + 2.5 MPa √ m
Colmonov5	$15.9 \pm 3.0 \text{ MPa} \sqrt{\text{m}}$
	$26.2 \pm 2.7$ MPa $\sqrt{m}$ (For another composition with increased Fe
	content due to dilution)

Although the chemical compositions of Stellite6 and Colmonoy5, reported in the above reference, are marginally different from that used in this work, this will not change the trend or the order of magnitude of the above values.

fracture toughness coefficient,  $K_{IC}$ , and (ii) the stacking fault energy (SFE).

As the damage during cavitation is caused by the repeating cyclic loading experienced on the material surface due to bubble collapse, it is reasonable to expect that a material with higher fracture toughness shall show better resistance to cavitation than a material with lower fracture toughness. As the damage during cavitation is due to the repeated cyclic loading of the material surface by the collapsing bubbles, it is reasonable to expect that a material with higher fracture toughness will show better resistance to cavitation damage than one with lower fracture toughness. Table 4 gives the average fracture toughness coefficients,  $K_{\rm IC}$ , of Stellite6 and Colmonoy5 at three different temperatures, viz. RT, 149 °C and 316 °C [32].

It is seen that  $K_{IC}$  value for Stellite6 is higher than that of Colmonoy5; therefore although the hardness of Colmonoy5 is marginally higher than that of stellit6, the cavitation damage resistance of Stellite6 is better than that of Colmonoy5 as is evident from the experimental results.

Stacking fault energy is the energy stored in the crystal lattice due to interruption in the stacking sequence of the constituent atoms. Cavitation erosion is characterized by high strain and high strain rates of the order of  $5*10^3$ /s [33]. In such high strain rate processes work hardening is opposed by dynamic recovery and the stacking fault energy of the structure plays an important role in the damage process.

Pure nickel has FCC structure while pure Co has HCP structure. The SFE of pure Ni  $(240 \pm 50 \text{ mJ/m}^2)$  [34] is higher than that of pure Cobalt  $(31 \text{ mJ/m}^2)$  [35]. The presence of alloying elements tend to lower the SFE further.

When SFE is low (as in Stellite6) there is a greater probability for stacking faults to occur and the area of the resulting stacking fault is high [36]. The mobility of dislocations is therefore reduced and deformation by cross slip and climb becomes more difficult producing less dynamic recovery because the partial dislocations have to first recombine before cross slip can occur. This results in higher degree of strain hardening and flow stress saturation at higher strain value and planar slip then becomes the dominant deformation mechanism.

On the other hand when the SFE is high as in Colmonoy5 (Nibase matrix) [37] cross slip occurs readily resulting in dynamic recovery, lesser degree of work hardening and saturation of flow stress at lower strain value. It is to be also noted that cobalt base alloys have an unstable FCC phase that transforms to HCP under mechanical stress/strain. In the case of Stellite6 this transformation in the base matrix absorbs some of the energy of collapse of cavitation bubbles resulting in reduced weight loss when compared to that in Colmonoy5.

The weight loss in Ni base alloys is therefore higher than that in Co base alloys under identical conditions.

The weight loss rate graph (Fig. 7) also shows that the damage rates for the various specimens have attained steady state (except for SS316L at 250 °C). It is also evident that the steady state weight loss rate exhibits a maximum at an intermediate temperature instead of a monotonic variation with temperature. Although the trend for SS316L looks different, it appears that the steady state weight loss rate at 250 °C will settle at a value higher than that at 200 °C.

The variation with temperature may be explained in terms of liquid properties. Increase in liquid temperature results in increase in the vapor pressure of the liquid and decrease in the equilibrium concentration of dissolved gas. Increased vapor pressure results in (i) increase in the bubble population/increase in bubble size at the end of expansion resulting in increase in damage (ii) increase in back pressure at the end of collapse resulting in decrease in damage. Decrease in equilibrium gas content results in a decrease in back pressure opposing collapse which results in increase in damage. These opposing effects manifests in the damage attaining a peak at an intermediate temperature.

# 5. Conclusions

Cavitation damage resistance of austenitic stainless steel and hard faced (with Colmonoy5 and Stellite6) variants in liquid sodium were determined experimentally.

The major conclusions from the present study are:

a. Cavitation resistance of both Stellite6 and Colmonoy5 deposits are significantly higher than that of 316L austenitic stainless steels in sodium. This confirms that hardfacing of the surfaces by any of these alloys can considerably reduce the extent of damage expected in components in FBRs which are likely to undergo cavitation in service.

- b. In austenitic stainless steel, cavitation damage occurs uniformly throughout the surface whereas in the hardfaced deposits, damage initiates at the interface of the matrix and the second phase particles.
- c. Co based Stellite alloy has better cavitation resistance than the Ni based Colomonoy5 alloy and this difference is attributed to higher fracture toughness of Stellite6 alloy than that of Colmonoy5 alloy and lower stacking fault energy of Co than that of Ni.

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