CHAPTER 5

RESULTS & DISCUSSION
CHAPTER 5 – RESULTS & DISCUSSION

5.0 INTRODUCTION

This chapter presents results of various tests described in Chapter 4. A comparison is made on the cavitation performance of SS 316L, Stellite 6 and Colmonoy 5 coatings. Weight loss resulting from cavitation damage is correlated with surface damage observed after the test, hardness of the deposit and other properties of the alloys. As cavitation damage is primarily estimated from weight loss measurements, an error analysis is first presented. Data acquired from the cavitation tests are in Appendix 2.

5.1 ERROR ANALYSIS [115]

The following measured variables influence the weight loss rate:

(i) Weight of specimen
(ii) Cover gas pressure
(iii) Temperature of liquid
(iv) Sodium level in cavitation vessel
(v) Operating frequency
(vi) Amplitude of displacement
(i) Error in weight measurement

The weight is measured to accuracy of 0.1 mg. Assuming the uncertainty to be normally distributed, the standard uncertainty (calculated based on the smallest weight measured) is,

\[ u_1 = \frac{0.1 \times 10^{-3}}{2} = 5 \times 10^{-5} \text{ g} = 5 \times 10^{-5} / 12.55 \times 100 = 3.98 \times 10^{-4} \% \]

(ii) Error in cover gas pressure

A Bourdon pressure gage is used to measure the pressure of cover gas in the cavitation vessel. The smallest pressure change that can be read from the gage is ±5 mbar. Assuming the uncertainty to be normally distributed, the standard uncertainty, \( u_2 = \frac{5}{2} = 2.5 \text{ mbar} = 2.5/100 \times 100 \) (for cover gas pressure of 100 mbar) = 2.5%.

(iii) Error in Temperature

The temperature of sodium in the vessel is measured using K type thermocouples spot welded to the vessel. The error in temperature measurement is ±1.5% of the reading. For a maximum temperature of 400 °C, error = 1.5/100*400 = 6 °C. Assuming the uncertainty to be normally distributed, the standard uncertainty, \( u_4 = \frac{6}{2} = 3 \text{ °C} = 3/400\times100 = 0.75 \% \)

(iv) Error in sodium level

The level of sodium in the cavitation vessel is measured by a resistance type spark plug level probe. The error in level measurement is ±1 mm. Assuming the uncertainty to be normally distributed, the standard uncertainty, \( u_3 = \frac{1}{2} = 0.5 \text{ mm} = 0.5/12 \times 100 = 4.1 \% \).

Since the absolute value of level (13 mm) is small this value is large. However, the range in the level permitted by ASTM G32 is 12±4 mm and this is achieved by keeping the inlet
valve ‘crack’ open while filling. For calculations, however, the uncertainty above is considered.

(v) Error in operating frequency

The operating frequency of 20 kHz is automatically controlled by the instrument to within ±0.5 kHz. Assuming the uncertainty to be normally distributed, the standard uncertainty, \( u_5 \frac{0.5}{2} = 0.25 \text{ kHz} = 0.25/20 \times 100 = 1.25 \% \)

(vi) Error in amplitude of displacement

The displacement amplitude of 50 μ is automatically controlled to within 2.5 μ. Assuming the uncertainty to be normally distributed, the standard uncertainty, \( u_6 \frac{2.5}{2} = 1.25 \mu = 1.25/50 \times 100 = 2.5 \% \).

Hence the combined standard uncertainty = \( \sqrt{2.5^2 + 0.75^2 + 4.1^2 + 1.25^2 + 2.5^2} = 5.6 \% \)

The expanded uncertainty based on a coverage factor of 2, providing a level of confidence of 95%, is 2*5.6 % = 11.2 %.

This error band is shown along with average value for weight loss measurements in the graphs.

5.2 RESULTS

5.2.1 Weight Loss

Table 5.1 gives details of the three different types of specimens employed in this study. It may be noted that hardness of the coatings is significantly higher than that of 316L material and among the two coatings Colmonoy5 has higher hardness. Further, although all the specimens

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were polished to have mirror finish on the eroding surface, the absolute surface roughness of Colmonoy 5 specimens, before start of testing, is higher than that for the other two types of specimens.

Table 5.1 – Properties of specimens

<table>
<thead>
<tr>
<th>Properties</th>
<th>SS 316 L</th>
<th>Hardfacing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposit thickness, mm (average)</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Hardness,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum value</td>
<td>96.4 HRB [112]</td>
<td>39.4 HRC [112]</td>
</tr>
<tr>
<td>Mean + SD (measured from 2 random samples in each type using FIE, model RASNE-1 digital Rockwell hardness tester)</td>
<td>95.61 ± 0.77 HRB (233 VHN)</td>
<td>38.64 ± 0.67 (369 VHN)</td>
</tr>
<tr>
<td></td>
<td>44.4 HRC [112]</td>
<td>40.69 ± 3.2 (393 VHN)</td>
</tr>
<tr>
<td>Absolute surface roughness, µm</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 2.5</td>
</tr>
</tbody>
</table>

The face of the specimen was polished to mirror finish (< 1 µm for SS316L and Stellite6 specimens and < 2.5 µm for Colomony5 specimen)

5.2.1.1 Austenitic Stainless Steel 316L

Cavitation tests were done in SS 316L at four temperatures viz. 200°C, 250°C, 300°C and 400°C. At 200°C three numbers of specimens, at 250°C two numbers of specimens, at 300°C three numbers of specimens and at 400°C one specimen were tested (Tables A2.1 – A2.9). Results of the weight loss measurements done on these specimens are given in Fig 5.1.
There is a marginal increase in weight loss with increase in temperature from 200 °C to 300 °C. However, weight loss is significantly lower for the specimen tested at 400 °C. Results indicate weight loss due to cavitation increases with increase in temperatures up to 300 °C and then decreases.

For a given temperature, the variation of weight loss with duration of testing is similar to that reported by Dayer [23] although the absolute values of weight loss in the present case are smaller than that reported in [23]. This could be due to the lower peak to peak amplitude of displacement employed for the present tests (viz. 25 μm, which is the alternate peak to peak displacement permitted in ASTM G32) compared to the value of 50 μm reported in [23]. Moreover, the operating frequency of the horn in the present tests is the ASTM G32 prescribed value of 20 kHz while that used in [23] is 15.5 kHz.
Fig. 5.2 shows the variation of rate of weight loss with time and Fig. 5.3 shows the variation of Mean Depth of Penetration Rate (MDPR) rate with temperature.

![Graph showing variation of weight loss rate in SS 316L with temperature.](image)

**Fig. 5.2 – Cumulative weight loss rate (CWR) vs cumulative time in SS 316L.**

MDPR is calculated using the formula

\[
\text{MDPR} \ (\mu \ / \ hr) = \frac{10^9 \Delta W}{(t \cdot A \cdot \rho)} \quad (2)
\]

where \(\Delta W\) = cumulative weight loss (gm) over a testing period of \('t'\) hrs, \(A\) is the area of the specimen face (m\(^2\)) and \(\rho\) is the density (kg/m\(^3\)) of the specimen at the testing temperature.

The entire area of the specimen face is used for the calculation.

As can be seen Table 5.1 the hardness of 316L is low compared to that of the hard faced coatings. During deformation under cavitation loading SS 316L undergoes work hardening and therefore during the initial stages the surface deforms easily and high damage rate occurs.
whereas with prolonged exposure the work hardening produced increases the hardness of the
damaged layer and stabilizes the damage rate (Fig. 5.2).

![Fig. 5.3 – Mean Depth of Penetration rate (MDPR) vs cumulative time in SS 316L](image)

It is seen from Figs. 5.2 and 5.3 that CWR and MDPR marginally increases when the
temperature is raised from 200 °C to 300 °C and then substantially decreases on increase of
temperature to 400°C indicating that the damage rate / MDPR tends to a maximum between
300°C and 400°C. The MDPR curves also show that the rates at 200°C, 250 °C and 400 °C have
attained steady state.

Review of published literature [23, 10] on cavitation erosion tests done in sodium using
vibratory device show that Dayer [23] has reported the occurrence of peak MDPR value in the
temperature range 200°C - 300°C while Hammit and Courbiere [10] have reported occurrence of
peak MDPR value in the range from 200°C - 400°C based on tests at CEA, Cadarache and three US laboratories.

5.2.1.2 Colmonoy 5 Hardfaced Coating

Cavitation erosion of Colmonoy5 in sodium was studied at four temperatures viz. 200°C, 250°C, 300°C and 400°C. At 200°C two nos., at 250°C three nos., at 300°C two nos. and at 400°C one nos. of specimen was tested (Tables A2.10 - A2.17). Fig. 5.4 shows the variation of cumulative weight loss with duration of testing for Colmonoy5. Fig. 5.5 shows the variation of rate of weight loss with time. The cumulative weight loss rate in the case of Colmonoy5 appears to be maximal between 250°C and 300°C. The MPDR is not shown as data for the density of Colmonoy5 at various temperatures is unavailable.

![Cumulative weight loss vs Time (Colmonoy5)](image)

**Fig. 5.4 – Cumulative weight vs cumulative time in Colmonoy5**
5.2.1.3 Stellite6 Hardfaced Coating

Weight loss measurements were carried out for Stellite6 specimens subjected to cavitation test at four temperatures viz. 200°C, 250°C, 300°C and 400°C. Two specimens each were tested at temperatures of 200°C and 250°C and one each at 300°C and 400°C. (Tables A2.18 – A2.23).

Fig. 5.6 below shows the variation of cumulative weight loss vs time for Stellite6. Fig. 5.7 shows the variation of rate of weight loss with time. Although the number of data points at 300°C is small, the peak erosion rate appears to be between 250°C and 400 °C. Hammitt and Courbiere [10] have reported a value close to 300°C.
Fig. 5.6 – Cumulative weight vs cumulative time in Stellite6

Fig. 5.7 – Cumulative weight loss rate vs cumulative time in Stellite6
5.2.1.4 Comparison between weight loss rates in SS316L, Colmonoy5 and Stellite6

Fig. 5.8 shows the comparison of the weight loss rates in SS 316L with the hardfaced specimens. Fig. 5.9 shows the comparison between weight loss rates in Colmonoy5 and Stellite6. 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.

Fig. 5.8 – Comparison of cumulative weight loss rate in SS316L, Colmonoy5 and Stellite6
5.2.2 Surface Damage

5.2.2.1 Austenitic Stainless Steel SS 316L

Fig. 5.10 shows the low magnification image of the specimen after testing. For short duration tests, a virtually unaffected rim is clearly visible (Fig. 5.10(a)) which is due to fluid dynamic edge effects [116, 117]. However, with extended duration the eroded area is observed to extend and cover almost the entire face of the specimen (Fig. 5.10(b)).
The presence of the undamaged rim, observed not only in stainless steel specimens but also in hardfaced specimens (Figs. 5.15, 5.16, 5.25, 5.26), is a characteristic of the bubble collapse mechanism in ultrasonic cavitation [118]. It is also seen that the damage increases from the periphery towards the central region of the specimen. The collapse of the bubbles in the periphery, initiated by the ultrasonic pressure variation, results in a propagation of the pressure wave towards the centre causing the bubbles near the centre to implode under larger pressure gradient resulting in higher damage near the centre than at the periphery. As the period of testing increases the peripheral portions also begin to show signs of erosion from the constant implosion of bubbles under the positive half of the oscillating ultrasonic pressure wave.

Also seen in Figs. 5.10 (b) is narrow annular regions in the periphery which have more damage than in the central region. This could be due to the presence of non uniform clusters of vapour bubbles on the surface of the specimen. The pattern of damaged regions of varying intensity is
similar to that reported by Dayer [23] on stainless steel specimens (Type 316 and 321) in liquid sodium using vibratory device operating at 15.5 kHz and 50 μ (peak to peak) amplitude.

Figs. 5.11 – 5.14 are the results of examination of the specimens under high magnification with a scanning electron microscope.

![Fig. 5.11 – SEM of polished sample before test](image)

(a) Near edge  
(b) Near middle  
(c) Near opposite edge

Fig. 5.12 – SEM of sample after 5 m 2 s

Fig. 5.11 is the SEM image of the specimen (in mirror finish condition) taken before test and Fig. 5.12 is the SEM images taken after 5 min. and 2 s. of testing in liquid sodium at 200°C. It is seen from Fig. 5.12 to Fig. 5.14 that in SS 316L the surface damage produced is predominantly ductile with deep pits and small sized craters. Fig. 5.12(b) is the SEM image of a
region near the centre of the specimen. The features of the crater (almost circular shape and raised rim around the crater) are indicative of the crater having been formed by the impact of liquid microjet which is in fact the predominant damaging mechanism in vibratory cavitation damage. Figs. 5.12(a) and (c) are SEM images of regions near the periphery on either side of the central region. It is seen that at the centre the pits are smaller than those at the edges and the particles breaking off from the surface are more fine grained. These SEM images also indicate that damage is not uniform over the surface and there are alternate regions of coarse and finely eroded regions. This is possibly due to (i) variation in ultrasonic cavitation from the centre towards the periphery (ii) progressive collapse of bubbles from the outer periphery towards the centre.

Fig. 5.13 and 5.14 are some more SEM images of SS 316 L specimen early on during the testing and after prolonged exposure to cavitation. These images help in understanding the mechanism of cavitation damage in austenitic stainless steel. It is seen that during the initial exposure to cavitation shallow and wide craters with rounded ridges at the periphery are formed which on subsequent exposure develop into deep narrow pits with sharp ridges.
It is seen from Fig. 5.13 (and also reported in literature [119]) 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 dimpled topography characteristic of damage in ductile materials. Fig. 5.14 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.

5.2.2.2 Colmonoy5 and Stellite6

Fig. 5.15 is a low magnification optical image Colmonoy5 specimen after testing in sodium at 250 °C for 6 m 7 s. The unaffected rim, present in SS 316L and Stellite5 specimens, is visible here also.
Fig. 5.16 is a low magnification optical image of Stellite6 specimen after testing in sodium at 200 °C for 7 m 23 s. The unaffected rim, similar to that for SS 316L specimen, is visible here.

| Fig. 5.15 – Colmonoy5 (C3) after testing in sodium at 250°C for 6 m 6 s | Fig. 5.16 – Stellite6 (S1) after testing in sodium at 200 °C for 7 m 23 s |

Fig. 5.17 to Fig. 5.19 are the results of examination of the specimen under high magnification with a scanning electron microscope. While Figs. 5.17 and 5.18 are the SEM images at early stage of cavitation damage (after ~ 6 min of testing), Fig. 5.19 is the image after prolonged exposure to cavitation.

Both the hardfaced coatings have a solidified dendritic microstructure. While in the case of Colmonoy5 the structure consists of borides and carbides dispersed in the interdendritic regions of a Ni base matrix phase, Stellite6 consists of interdendritic Cr rich carbides dispersed in Co rich matrix phase dendrites.

For Colmonoy 5 deposits it may be seen that damage is initiated at the interface between the hard second phase (borides or carbides) and the matrix. Figure 5.18 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. 5.19. Also evident is severe deformation of the base matrix.

Dendrite phases and initiation of material removal at interdendritic regions

**Fig. 5.17 – Colmonoy5 sample (C3) – After cavitation in sodium (period = 6 min 6 secs, Temp = 250 °C**

Flower like dendrite phases; material removal begins at hard interdendritic regions.

**Fig. 5.18 – Colmonoy5 sample (C3) – After cavitation in sodium (period = 6 min 6 secs, Temp = 250 °C**

The voids are regions where the borides and carbides and portions of the base matrix are removed.

**Fig. 5.19 – Colmonoy5 sample (C3) – After cavitation in sodium (period = 41 min, Temp = 250 °C**
| Voids formed by removal of carbides | Further exposure results in damage propagation to the work hardened matrix
Fig. 5.20 – Stellite6 sample (S2) – After cavitation in sodium (period = 7 min 31 secs, Temp = 250 °C) | Fig. 5.21 – Stellite6 sample (S2) – After cavitation in sodium (period = 42 min, Temp = 250°C) |

Figs. 5.20 and 5.21 are SEM images of the stellited specimen at an early stage and after prolonged exposure respectively. As in the case of Colmonoy5 deposit, damage begins in Stellite6 deposit also at the interface between carbides and the matrix. With the progress of cavitation, the carbides get dislodged from the surface initiating cracks in the work hardened matrix and subsequent weight loss. However, the deformation observed for the matrix phase is significantly different from those observed in the case of Colmonoy and the austenitic stainless steel.

### 5.2.3 Absolute Surface Roughness

The progression in absolute surface roughness of the three materials tested was analysed for a few specimens tested at 200 °C. The absolute surface roughness of the selected specimens
was measured by means of a non-contact type optical profiler prior to start of testing and after every test thereafter. The results are shown in Fig. 5.22 and Fig. 5.23.

![Diagram showing Absolute Roughness vs Time for SS316L vs Colmonoy5 vs Stellite6.](image)

**Fig. 5.22** – Progression of absolute surface roughness with cavitation damage (200 °C)
Fig. 5.23 – Comparison of progression of absolute surface roughness for Colmonoy5 and Stellite6 (200 °C)

It is seen from a comparison of Fig. 5.22 with Fig. 5.8 and Fig. 5.23 with Fig. 5.9 that the absolute surface roughness is as much an indicator of relative ranking of resistance of materials to cavitation damage as is cumulative weight loss rate from cavitation.

Figs. 5.24 and 5.25 are plots of absolute surface roughness against cumulative weight loss rate. These figures corroborate the above conclusion that absolute surface roughness is a good indicator of cavitation damage resistance.
Fig. 5.24 – Comparison of absolute surface roughness and cumulative weight loss rate for all materials

Fig. 5.25 – Comparison of absolute surface roughness and cumulative weight loss rate for SS316L
5.3 DISCUSSION

The marked reduction in the weight loss produced in the hard faced specimens compared to that produced in SS 316L may be attributed to the large variation in hardness between SS316L (HRB 95.6) and the hardfaced variants, viz. HRC 38.6 for Stellite6 and HRC 40.7 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 fracture toughness coefficient, $K_{IC}$, and (ii) the stacking fault energy (SFE).

As the damage during cavitation is caused by the repeating cyclic loading on the material surface due to bubble collapse, it is reasonable to expect that a material with higher fracture toughness will show better cavitation resistance than a material with lower fracture toughness. Table 5.2 gives the average (of three different temperatures, viz. room temperature, 149 °C and 316 °C) fracture toughness coefficients, $K_{IC}$, of Stellite6 and Colmonoy5 [120].
Table 5.2 – Fracture toughness coefficients of Stellite6 and Colmonoy5

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Stellite6</td>
<td>$35.6 \pm 2.5$ MPa $\sqrt{m}$</td>
</tr>
<tr>
<td>Colmonoy5</td>
<td>$15.9 \pm 3.0$ MPa $\sqrt{m}$</td>
</tr>
<tr>
<td></td>
<td>$26.2 \pm 2.7$ MPa $\sqrt{m}$ (for another composition with increased Fe content due to dilution)</td>
</tr>
</tbody>
</table>

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.

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 stellite6, 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 [29]. 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.

Colmonoy is a Ni base alloy while Stellite is a Co base alloy. Pure nickel has FCC structure while pure Co has HCP structure. The SFE of pure Ni ($240 \pm 50$ mJ/m$^2$) [121] is higher than that of pure Cobalt ($31$ mJ/m$^2$) [122]. 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 [123]. The separation distance between adjacent partial dislocations is then large and the recombination of partial dislocations becomes difficult. The mobility of dislocations is thus reduced and deformation by cross slip and climb becomes 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 (Ni-base matrix) cross slip occurs readily resulting in dynamic recovery, lesser degree of work hardening and saturation of flow stress at lower strain value. This is evident from the difference in the surface topography of the damaged surface as seen in Fig. 5.19 for Colmonoy 5 and Fig. 5.21, for Stellite 6 respectively.

Another mechanism that affects the damage resistance of Stellite is the change in structure of the matrix. Pure Co exists in two allotropic forms, viz low temperature HCP and high temperature FCC [124]. However, Stellite (which is a Co rich solid solution alloyed with Cr, W and C) retains its FCC phase even at lower temperatures (the alloying elements Cr and W increase the transformation temperature). Low temperature deformation under high stress induces FCC to HCP transformation depending on the SFE of the alloy and the temperature of deformation. This transformation absorbs some of the bubble collapse energy and results in work hardening of the surface thus reducing the weight loss due to cavitation damage. It is to be also noted that HCP structure has less operative slip systems when compared to FCC structure. This could also be the reason for the differences in the topography of the damage observed in Colmonoy 5 and Stellite 6 hardfaced coatings (Fig. 5.19 vis-à-vis Fig. 5.21).
Analysis of wear debris in cavitation erosion tests [124] on Stellite6 has shown that not only is the structure of the debris largely HCP but also that the volume fraction of HCP on the surface of the Stellite6 test sample is found to significantly increase during the course of the test thus giving credence to the conclusion that the cavitation damage resistance of Stellite6 is derived from the matrix and improved by the FCC to HCP transformation.

The resistance to cavitation damage in Co base alloy such as Stellite6 is therefore higher than that in Ni base alloy such as Colmonoy5.

5.3.1 Effect of temperature

The variation with temperature may be explained in terms of liquid properties. Increase in liquid sodium temperature results in (a) increase in the vapor pressure of the liquid (ii) increase in the liquid compressibility (iii) reduction in the density, surface tension, viscosity and dissolved gas content.

Increase in vapor pressure results in (i) an increase in the bubble population / increase in bubble size at the end of expansion in which tends to increase the energy transferred to the solid at the end of collapse thereby resulting in increased damage (ii) increase in back pressure at the end of collapse which tends to oppose collapse thereby resulting in reduced damage.

Increase in liquid compressibility reduces the energy transferred to the solid thereby reducing damage. Similarly reduction in density limits the transfer of energy to the solid.

Reduction in viscosity permits expansion of the bubble to a larger size and enables more complete collapse while reduction in surface tension aids expansion and opposes collapse.

Decrease in equilibrium gas content reduces the back pressure opposing collapse thereby increasing damage.
The net effect of the above factors results in the MDPR attaining a peak value at an intermediate temperature between melting point and boiling point. As mentioned earlier, peaking of MDPR, at a temperature between melting point and boiling point, in tests with ultrasonic vibratory device sodium is also reported in literature [23, 10]. It may be noted that this is also observed in tests in water wherein the peak value of MDPR occurs approximately midway between the melting point and the boiling point [125].

The effect of temperature was studied by solving the Gilmore equation (3.16) for four different temperatures, viz. 150°C, 200°C, 300°C, 400°C and 500°C. The damaging pressure was computed using equation 3.29. The results are summarized in Table 5.3.

**Table 5.3 – Effect of temperature on jet velocity and collapse pressure - From solution of Gilmore’s equation**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Temp. °C (K)</th>
<th>Vel of sound, m/s</th>
<th>Max radius, mm</th>
<th>Min. radius, μm</th>
<th>Jet velocity, m/s</th>
<th>Collapse pressure, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150 (423)</td>
<td>2480</td>
<td>1.36</td>
<td>17.2</td>
<td>1854</td>
<td>4202</td>
</tr>
<tr>
<td>2</td>
<td>200 (473)</td>
<td>2460</td>
<td>1.35</td>
<td>17.1</td>
<td>1892</td>
<td>4201</td>
</tr>
<tr>
<td>3</td>
<td>300 (573)</td>
<td>2411</td>
<td>1.34</td>
<td>16.6</td>
<td>1995</td>
<td>4234</td>
</tr>
<tr>
<td>4</td>
<td>400 (673)</td>
<td>2361</td>
<td>1.32</td>
<td>17.9</td>
<td>1897</td>
<td>3846</td>
</tr>
<tr>
<td>5</td>
<td>500 (773)</td>
<td>2313</td>
<td>1.31</td>
<td>26</td>
<td>1390</td>
<td>2680</td>
</tr>
</tbody>
</table>
It is seen from Table 5.3 that the collapse pressure is more or less the same between 150°C and 300°C and decreases with further increase in temperature. In the solution of Gilmore's equation the effect of liquid properties such as density, vapor pressure, viscosity, surface tension and compressibility is accounted. However, the effect of heat transfer between the bubble contents and the liquid and the effect of dissolved gas content are not considered. Moreover, no consideration of the distribution of bubbles is made. These effects will influence the cushioning effect of surrounding bubbles on the collapse pressure and affect both the magnitude and variation in damage with temperature.

The normal operating temperature of the cold pool in PFBR is 397 °C and the hot pool is 547 °C. The above results indicate that for components in the cold pool the damage due to cavitation under normal operation will be lower than the maximum damage rate.

5.4 COMPARISON OF DAMAGE IN SS316L, COLMONOY5 AND STELLITE6 SPECIMENS

<table>
<thead>
<tr>
<th>Material</th>
<th>Time (min)</th>
</tr>
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<tbody>
<tr>
<td>SS 316L(A15)</td>
<td>55</td>
</tr>
<tr>
<td>Colmonoy5(C3)</td>
<td>41</td>
</tr>
<tr>
<td>Stellite6(S3)</td>
<td>46</td>
</tr>
</tbody>
</table>

Temperature - 250°C

Fig. 5.26 – Comparison of cavitation damage produced in SS 316L, Colmonoy5 and Stellite6
Fig. 5.26 is a comparison of SS 316L, Colmonoy5 and Stellite6 specimens after testing at 250 °C for ~ 1 hr while Fig. 5.27 is a comparison of SS 316L, Colmonoy5 and Stellite6 specimens after testing at 400°C for 1 hr.

<table>
<thead>
<tr>
<th>SS 316L</th>
<th>Colmonoy5</th>
<th>Stellite6</th>
</tr>
</thead>
<tbody>
<tr>
<td>After testing for 1 h at 400°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5.27 – Comparison of cavitation damage produced in SS 316L, Colmonoy5 and Stellite6**

From the Figs. 5.26 & 5.27 the marked reduction in cavitation damage with hardfacing is evident. Also clear is the improved resistance of Stellite6 to cavitation damage vis-à-vis Colmonoy5.