CHAPTER 6

EVALUATION OF DRY SLIDING WEAR RATE AND
ANALYSIS OF RESIDUAL STRESS

6.1 INTRODUCTION

This chapter concentrates on the dry sliding wear behaviour of PTA hardfaced overlay as a function of wear testing parameters such as applied load (L) and sliding velocity (U) and the amount of PTA heat input. The effects of wear testing parameters and the amount of PTA heat input (Q) on wear rate are explained clearly in this chapter by conducting fifteen trial run using Box-Behnken design matrix. The effects of wear testing parameters and PTA heat input on wear rate are presented in graphical form for quick analysis. Also, this chapter presents the residual stresses analysis in the high heat input hardfaced gate valve using FE simulation (contour method). The simulated values are verified by the experimental results as measured at the surface of the hardfaced gate valve using XRD technique.

6.2 EXPERIMENTAL PROCEDURE

6.2.1 Wear Test

Dry sliding wear tests were conducted at room temperature (30°C) using a pin-on-disc type of machine. Cylindrical pins of 3 mm diameter and 25 mm long were extracted from the hardfaced gate valves with the help of EDM. To ensure a constant surface finish, the hardfaced surface of each pin was carefully smoothened to a final average roughness $R_a$ of 0.4 $\mu$m. The disc
was made of SiC, with a grid size of 250 μm and a hardness of 2800 HV. Generally, the hardness of disc material is higher than the hardness of specimen. Before the experiments, both the pin and the disc were carefully cleaned with acetone solution. The surface of the disc was lapped with a diamond suspension of 15 μm. The lapping procedure was repeated after each test. The disc was installed in the machine chuck to slide against the mating pin which was mounted in the holder. Each test was performed on a new track on the disc. The test setup is illustrated in Figure 6.1.

![Figure 6.1 Pin-on-Disc Wear Testing Machine](image)

In wear testing, the relationship between wear and friction was observed by several authors (Oktay and Suh 1992, Berger et al 1997, Bhushan 1999, Aoh and Chen 2001, Celik and Kaplan 2004, Modi et al 2004, Vite et al 2005, Marimuthu 2006) that the variation of wear rate and friction depends on the interfacial conditions such as normal load, geometry, relative surface motion, sliding speed, surface roughness of the rubbing surfaces, type of material, system rigidity, temperature, stick slip, relative humidity, lubrication and vibration (Yang and Loh 1995, Shanmugam 2005, Marimuthu 2006).
Among these factors Heat input (Q), Applied load (L), and Sliding velocity (U) are the major factors that play a significant role for the variation of wear rate, as given in Table 6.1.

**Table 6.1 Parameters Considered for Wear Test and their Levels**

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameter</th>
<th>Symbol</th>
<th>unit</th>
<th>Factor levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heat input</td>
<td>Q</td>
<td>kJ/cm</td>
<td>8 11 14</td>
</tr>
<tr>
<td>2</td>
<td>Normal load</td>
<td>L</td>
<td>N</td>
<td>5 10 15</td>
</tr>
<tr>
<td>3</td>
<td>Sliding velocity</td>
<td>U</td>
<td>m/sec</td>
<td>0.01 0.02 0.03</td>
</tr>
</tbody>
</table>

A computer controlled wear and friction monitor (Model TR 20) manufactured by M/s DUCOM, Bangalore and installed in the Department of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore was used for conducting the experiments. A Box-Behnken design matrix shown in Table 6.2, consisting of 15 sets of coded conditions was selected to conduct the experiments. Box-Behnken design uses the selection of corner, face and central points to span an experimental space with fewer points than a Complete Factorial Design (CFD). It has not possessed the extended axial points, hence it uses only three level factors (Cochran and Cox 1963). The experiments were conducted as per design matrix at random to avoid systematic errors creeping into the system. The wear rate of hardfaced overlay was directly deduced from vertical displacement of pin in terms of weight loss. Then, the weight loss was divided by the density of the sample to obtain the volume loss. Wear rate was calculated by dividing the volume loss by the sliding distance traversed. A Mettler micro-balance was used for weighing the specimen. Specimen was cleaned with acetone prior to and after the wear test. The estimated wear rates are listed in Table 6.2. Typical specimens after completion of wear test are shown in Figure 6.2.
6.2.2 Residual Stresses

The high heat input (trial number 19) hardfaced gate valve was taken for conducting the residual stress measurements. The residual stress measurements were carried out on the hardfaced gate valve using
(i) XRD technique and

(ii) Contour method.

6.2.2.1 XRD Technique

After stress relieving the hardfaced gate valve, the oxide films were removed using emery paper and then electrochemical polishing was done on the locations at which residual stress measurements were to be carried out. Those locations are shown in Figure 6.3. The residual stress measurement which was executed using X-ray stress analyzer (Rigaku strainflex MSF -2M) having a back reflection type goniometer with a 2θ scan range from 140°C to 170°C. The strain in the surface layer was estimated by measuring peak shifts due to deformation of the crystal lattice using CuKα radiation. Finally these strains were converted into stresses by assuming linear elastic distortion of the crystal lattice.

Figure 6.3 Location of Residual Stress Measurement using XRD Technique
6.2.2.2 Contour Method

The measurement of residual stresses on the hardfaced gate valve using contour method primarily involves three steps:

- Specimen cutting
- Contour measurement and
- Modelling and estimation of residual stresses.

6.2.2.2.1 Specimen Cutting

Specimen cutting is the first and the most critical step in the contour method. The cutting process was carried out in wire cut EDM using 0.1 mm diameter brass wire and it was assumed that there was no plastic deformation and material removal. The single flat cut without any physical contact (non contact approach) between the wire and the part being machined, helps to avoid any localized plastic deformation compared to conventional machining (Prime 2001) and helps to achieve high accuracy. The entire cutting process was completed in 3 hours. Figure 6.4 shows the cross section of the hardfaced gate valve after cutting by wire cut EDM.

![Cross Section of the Hardfaced Gate Valve after Cutting by Wire Cut EDM](image-url)
6.2.2.2 Contour Measurement

After the wire cut, the surface deforms owing to the release of residual stresses. The deformed surface was measured by SPECTRA model Coordinate Measuring Machine (CMM) which was used to measure the contour of complex shapes with high accuracy in the order of 3 microns. Probe tip of 1 mm diameter and 10 mm length is used for locating coordinates in deformed surface. Figure 6.5 shows the CMM with touch trigger probe. The measurement points were taken with reference to XYZ coordinates upto 10 mm depth from one side of gate valve. The displacements measured from one side of both halves were averaged and the average value was used for calculating the original residual stresses.

Figure 6.5 CMM with Touch Trigger Probe

6.2.2.3 Finite Element Modelling and Stress Analysis

Finite element modelling and analysis using ANSYS 10.0 were performed to calculate the original residual stresses released. Due to symmetry, only one eighth of the portion was considered for residual stress analysis. The nodes were created by Direct Node Generation technique with 0.5 mm increment along longitudinal direction (X – direction), 1 mm increment along transverse direction (Y – direction) and variable depth
(Z – direction) up to 10 mm thick from hardfaced surface. The remaining 15 mm thickness was modelled similarly, with 1 mm increment along X, Y and Z directions. Using those nodes, SOLID 45 elements having eight nodes and three degrees of freedom were generated. The generated model of hardfaced gate valve had total nodes of 13304 as shown in Figure 6.6. Out of these 13304 nodes, only nodes of hardfaced layer are considered for estimation of the residual stresses.

![Figure 6.6 Meshed Model of Hardfaced Gate Valve](image)

The governing equation used in the structural static linear Finite Element model is

\[
[K_T] \{ \Delta u \} = \{ F \} \quad (6.1)
\]

Where

- \([K_T]\) - Tangent stiffness matrix
- \{ \Delta u \} - Displacement
- \{ F \} - Load

The boundary conditions are

\[ u(x) = v(y) = 0 \text{ and } w = w(z) \]
The displacement measured along Z direction using CMM was applied as a displacement in the meshed static structural model to calculate the amount of residual stresses present in the gate valve. The young’s modulus and poison’s ratio of substrate and stellite 6 are 209 GPa and 0.29 and 210 GPa and 0.25 respectively.

6.3 DEVELOPMENT OF WEAR RATE MODELLING

The regression equation representing the wear rate of the hardfaced overlay was developed as explained in sections 3.5.1 and 3.5.2. The regression equation in coded form is given in equation (6.2).

\[
\text{Wear rate} = 32.000 + 8.375Q + 10.625L + 7.750U - 0.875Q^2 + \\
1.125L^2 + 1.375U^2 + 5.750QL + 3.000QU + 6.500LU
\]

(6.2)

Insignificant coefficients were eliminated as explained in section 3.5.3 and the final model was constructed using only those significant coefficients. The models thus obtained are given in coded form in equation (6.3).

\[
\text{Wear rate} = 32.867 + 8.375Q + 10.625L + 7.75U + 5.75QL + \\
3.000QU + 6.500LU
\]

(6.3)

The above model in natural form is given in equation (6.4).

\[
\text{Wear rate} = 48.886 - 1.903Q - 5.901L - 0.311U - 0.375QL + \\
0.019QU + 0.026LU
\]

(6.4)

The R-Sq, adjusted R-Sq and SE of the final model were estimated and presented in Table 6.3. From the table, it is evident that the regression model is quite accurate (Ramasamy et al 2002). The adequacy of the model so
developed was also tested by using the ANOVA which is presented in Table 6.4. It could be observed that the calculated values of ‘F-ratio’ are greater than the tabulated value at 95% confidence level, and hence the model is adequate.

**Table 6.3** Values of R-Sq, Adj. R-Sq and SE of the Developed Model for Wear Rate

<table>
<thead>
<tr>
<th>Response</th>
<th>Full Model</th>
<th>Reduced Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R-sq</td>
<td>Adj. R-sq</td>
</tr>
<tr>
<td>Wear rate</td>
<td>0.964</td>
<td>0.898</td>
</tr>
</tbody>
</table>

**Table 6.4** ANOVA for Checking the Adequacy of the Developed Model for Wear Rate

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>Degree of freedom</th>
<th>Means square</th>
<th>F-Ratio</th>
<th>P-value</th>
<th>Adequacy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>2282.000</td>
<td>6</td>
<td>380.333</td>
<td>29.908</td>
<td>0.000</td>
<td>Adequate</td>
</tr>
<tr>
<td>Residual</td>
<td>101.733</td>
<td>8</td>
<td>12.717</td>
<td>3.58</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The validity of the model is further tested by drawing scatter diagram as shown in Figure 6.7. The observed values and predicted values of the models are scattered close to 45° line, indicating an almost perfect fit of the developed empirical model.
Experiments were conducted to verify the developed regression equations. Two confirmity runs were made using different values of the wear testing parameters and amount of heat input, other than one used in the design matrix. Experimental values of the wear rate were compared with the predicted values of the wear rate from the model, represented in Table 6.5, and it is observed that the error in the predicted models is ± 1% at 95% confidence level.

Table 6.5 Results of Confirmity Experiments for Wear Rate

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Wear rate $x10^{-12}$ m$^3$/m</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q</td>
<td>L</td>
<td>U</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Average 0.545
6.4 RESULTS AND DISCUSSION

6.4.1 Effects of Wear Testing Parameters and PTA Heat Input on Wear Rate

The effects of wear testing parameters and PTA heat input on wear rate were obtained from the regression models presented graphically in Figures 6.8 and 6.9.

6.4.1.1 Direct Effects of Wear Testing Parameters and PTA Heat Input on Wear Rate

Figure 6.8 shows the direct effects of wear testing parameters and PTA Heat Input on wear rate. It is evident from the figure that wear rate increases with increase in heat input, applied load and sliding velocity. It could be due to increase in dilution with increase in heat input producing larger size of grains in the microstructure resulting in more wear rate (Atamert and Bhadeshia 1989, Frenk and Kurz 1994, Kian et al 1995, So et al 1996, De

![Figure 6.8](image)

**Figure 6.8** Direct Effects of Wear Testing Parameters and PTA Heat Input on Wear Rate
Mol Van Otterloo and De Hosson 1997, Shin et al 2003, Celik and Kaplan 2004, Vite et al 2005, Lin and Chen 2006). The increase in applied load generates high interface (flash) temperatures between the contacting surfaces which soften the material that can significantly reduce the strength of the materials (Bhushan 1981) and correspondingly increase the wear rate. The increase in wear rate with increase in sliding velocity is due to higher shear strain rate has resulted in increase in real area of contact (Yang and Loh 1995, So et al 1996, Aoh and Chen 2001).

6.4.1.2 Interaction Effect of Applied Load and Sliding Velocity on Wear Rate

Figure 6.9 shows the interaction effect of applied load and sliding velocity on wear rate. It is clear from the figure that wear rate increases with increase in applied load at all levels of sliding velocity. The rate of increase in wear rate with increase in applied load increases with increase in sliding velocity. This is mainly caused by the combined effects of applied load and

Figure 6.9 Interaction Effect of Applied Load and Sliding Velocity on Wear Rate
sliding velocity which generates higher flash temperature between the mating surfaces resulting in increased wear rate.

### 6.4.2 Analysis of Residual Stresses

#### 6.4.2.1 Residual Stress Analysis by Contour Method

Figure 6.10 shows the residual stress distribution on hardfaced gate valve using contour method. From the figure, it is found that the stress reaches a maximum value of 232 MPa at a distance of 4 mm from the beginning of hardfaced overlay and then decreases. It becomes compressive residual stress as the distance increases. The maximum compressive residual stress of 280 MPa is found at a distance of 16 mm from the hardfaced overlay.

#### 6.4.2.2 Residual Stress Measurement by XRD Technique

Figure 6.11 shows the residual stress distribution on the surface of hardfaced gate valve using XRD Technique and contour method. From the figure, it is clear that the same trend was observed by XRD technique. The maximum compressive residual stress value of approximately 293 MPa was obtained at the distance of 16 mm from the hardfaced overlay. The maximum tensile residual stress value of 241 MPa is found at a distance of 4 mm from the beginning of the hardfaced overlay. These values were compared with allowable limits of yield strength of stellite 6 (550 MPa), it is low due to the stress relieving of gate valve after hardfacing. The residual stress analysis by contour method was compared with the XRD technique, showed a good agreement between them.
Figure 6.10 Residual Stress Distribution in 2” Hardfaced Gate Valve

Figure 6.11 Distribution of Residual Stresses
6.5 CONCLUSION

Based on the experimental analysis the following conclusions are derived.

- Wear rate increased with increase in heat input, applied load, and sliding velocity.

- The interaction effect of applied load and sliding velocity on wear rate were found significant.

- The surface residual stresses were measured in the circular overlay bead geometry of hardfaced gate valve using XRD technique and contour method. The results obtained from the contour method were compared with the experimental results obtained from XRD technique. It was found that residual stresses obtained by contour method had good agreement with the residual stresses measured by XRD technique.