A systematic methodology to characterise the running-in and steady-state wear processes

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Abstract
An improved methodology has been developed to characterise running-in and steady-state wear processes. The experimental study was conducted with En 31 steel specimens on reciprocating tester with ball-on-flat geometry under lubricated sliding conditions. The tests were conducted according to a factorial design. The variables selected were the load, temperature and surface roughness. The wear behaviour for a given set of operating conditions has been characterised on the basis of developed methodology. The parametric influence of operating conditions was then analysed on the basis of polynomial relationships. The steady-state wear was found to be significantly influenced by the initial roughness.

Keywords: Running-in, Steady-state wear, Least square method

1. Introduction
Numerous investigations are being conducted to study the running-in and steady-state wear behaviour of tribological components [1-5]. Such studies are important in ensuring efficient operation and long life of the components. Several criteria can be employed to characterise the completion of running-in. These include stable roughness, steady friction and steady wear [6]. The present paper deals with the commonly observed behaviour involving running-in followed by steady wear. Typical behaviour is given in Fig. 1. After a long duration of steady-state wear there can be a transition to ‘wear out’ zone where useful life of the component ends. The present work deals only with the running-in and steady-state parts of the curve.

Typical plots of wear behaviour with running time can be used to approximately assess the processes involved. But estimates based on a proper mathematical model and statistical procedures give a more precise quantification of running-in and steady-state wear rates. Such improved precision is important in distinguishing the influence of operating conditions and lubricants especially when the changes are small. For example if a new lubricant can decrease the wear rate of an engine the estimation of the change can be difficult unless precise approaches are followed. In the present paper, available mathematical formulation of the running-in and steady-state wear by Zheng et al. [4] was adopted. The coefficients in the mathematical expression are of non-linear nature. A new methodology has been developed to estimate the coefficients. Methodology for the running-in period has also been developed in this work.

The above methodology has been utilised to analyse the experimental wear data. The experiments were conducted with En 31 steel specimens in a reciprocating tester with ball on flat geometry under lubricated sliding conditions. Influence of load, temperature and roughness on wear behaviour were studied utilising factorial design. Wear behaviour was first quantified at each set of operating conditions by the developed mathematical model. Parametric influence was then estimated by developing polynomial expressions. The study showed that initial roughness of the flat specimen has significant influence on the steady-state wear. This is despite the fact that final roughness obtained in all the cases was similar.

2. Theoretical modelling of wear behaviour
The variation of wear rate of a new component with time has been shown schematically in Fig. 2. Initially the wear rate is high which reduces exponentially with time and reaches steady-state after some time. This information may be mathematically expressed as follows [4]:

\[ \dot{v} = \gamma v_0 - \alpha e^{-bt} + \dot{v}_0 \]  

(1)

In the above equation, coefficient \( b \) has inverse relation with running-in period. The influence of \( b \) is illustrated in Fig. 2.
Nomenclature

\[ a \] an integration constant
\[ b \] non-linear coefficient having inverse relation with running-in period
\[ d \] diameter of ball scar (mm)
\[ d_0 \] Hertzian diameter of circular contact supporting the load before wear (mm)
\[ d_1, d_2 \] diameter of ball scar along and across the sliding direction (mm)
\[ E, E_1, E_2 \] elastic constants of materials 1 and 2, respectively (N/mm²)
\[ E^* \] relative elastic constant of the two surfaces (N/mm²)
\[ l \] average length of disc scar (mm)
\[ m \] number of wear volume measurement during the wear test (10)
\[ n \] number of set of operating condition (9)
\[ P \] normal load (N)
\[ P_{ij} \] normal load at jth set of operating condition (N)
\[ r \] relative radius of the two surfaces at contact area before wear (mm)
\[ \gamma \] relative radius of the two surfaces at contact area before wear, respectively (mm)
\[ R \] rms roughness of the surface (\( \mu m \))
\[ R_{e1}, R_{e2} \] roughness at jth set of operating condition (\( \mu m \))
\[ s \] time (h)
\[ t_j \] running-in period (h)
\[ t_{ij} \] running-in period at jth set of operating condition (h)
\[ T_b \] bulk temperature (°C)
\[ T_c \] contact temperature at jth set of operating condition (°C)
\[ v \] wear volume (mm³)
\[ v_{ball}, v_{disc} \] wear volume of ball and disc scar, respectively (mm³)
\[ v_0 \] wear volume of ball scar at time \( t \) (mm³)
\[ v_i \] wear volume at time \( t_i \) from predictor Eq (5) (mm³)
\[ p \] average of all \( v_i \), \( i \) varies from 1 to 10 (mm³)
\[ r \] wear rate (mm/h)
\[ \omega \] steady-state wear rate at time infinity (mm/h)
\[ \omega_{ij} \] steady-state wear rate at jth set of operating condition (mm/h)
\[ w \] average width of disc scar (mm)

Greek letters

\[ \sigma_2 \] Poisson’s ratio of surface 1 and 2, respectively
\[ \varepsilon \] frictional temperature rise based on geometric contact area (°C)

Curve 1 corresponds to a higher \( b \) value in comparison to curve 2. In the case of curve 1 the running-in is faster.

Another available model of Lin and Cheng [7] considered that the variation in wear rate as a function of time is related to the average shear force \( I \) of a thin layer near the surface and its shear strength \( S \). It is difficult to assess these changes in the near surface layer. The overall variation given by the authors is

\[
I(t) = I_0 - I_s e^{-\eta t} + I_s
\]  

where \( I_0 \) is the initial value of \( I \), and \( I_s \) its steady-state value, \( \eta \) relates to the duration of friction behaviour before reach-

Fig. 1. Wear behaviour of new component in its life span. (I) Running-in zone; (II) steady-state wear zone; (III) wear out zone.
ing steady-state. Wear rate at time \( t \) is considered to be proportional to \( I(t) \). Thus, this equation is similar in its overall nature to the equation adopted above.

Putting \( t = 0 \) and \( t = \infty \) in Eq. (1) we get \( \lambda Q \) and \( v_s \) respectively, which satisfy boundary conditions of the wear process. Integrating Eq. (1) with respect to time \( t \), we get

\[
\lambda(t) = -\left( \frac{\lambda_0 - \lambda_s}{b} \right) e^{-bt} + v_s t + a
\]

At \( t = 0 \), wear volume, \( v = 0 \). Putting this condition in Eq. (3) we get

\[
a = \frac{\lambda_0 - \lambda_s}{b}
\]

Combining Eqs. (3) and (4) we find

\[
(5)
\]

or,

\[
(6)
\]

For steady-state at \( t = \infty \),

\[
n = a + v_s t
\]

In Eq. (6), \( v \) is non-linear in terms of coefficients \( a, b \), and \( v_s \). This equation was linearised by assuming value of \( b \) and then calculating \( a \) and \( v_s \) from the least square method given by following equation:

\[
[A] = \langle X'X \rangle^{-1}X'Y
\]

The \( X, Y \) and \( A \) matrices are

\[
X = \left[ \begin{array}{c} 1 - e^{-b t_1} \\ 1 - e^{-b t_2} \\ \vdots \\ 1 - e^{-b t_m} \end{array} \right], \quad Y = \left[ \begin{array}{c} v_1 \\ v_2 \\ \vdots \\ v_m \end{array} \right], \quad A = \left[ \begin{array}{c} a \\ \lambda_0 \end{array} \right]
\]

where \( m \) is the number of wear volume measurement during the wear test.

The flow chart for calculating non-linear coefficients \( a, b \) and \( v_s \) iteratively. The value of \( b \) corresponds to the condition where \( (1 - R) \) is negative while \( b \) corresponds to the condition where \( (1 - R) \) is positive. The correlation coefficient, \( R \) is calculated by the following formula [8]:

\[
R = \sqrt{\frac{\sum_{i=1}^{m} (v_i - \bar{v})^2}{\sum_{i=1}^{m} (v_i - \bar{v})^2}}
\]

Then bisection method is used to find the value of \( b \) iteratively after fixing the criteria that \( |(1 - R)| < 1 \times 10^{-4} \) so that correlation coefficient \( R \) is very small value and selected as \( 1 \times 10^{-4} \) so that correlation coefficient \( R \) approaches unity. This methodology finally gives the value of \( a, b, v_s \), running-in wear rate \( \lambda Q \) and steady-state wear rate \( v_s \).

The running-in period \( t_r \) is calculated by defining it as the time at which \( v_s = (\mu p/100) \) where \( p \) is the percentage. This may be expressed mathematically by the following equation:

\[
t_r = \frac{-\log_2(1/100)}{1 - \mu p} \]  

The above model has been applied to the experimentally determined wear behaviour as described later.

3. Experimentation

The present study was conducted on SRV Optimol reciprocating tester (Fig. 4). In this tester, the parameters that can be varied are load, frequency, environment, temperature and stroke length. Instantaneous frictional force during each cycle is displayed on CRO while the average coefficient of friction is plotted on the recorder. In this machine the upper ball reciprocated on the stationary lower specimen. The lower specimen was a disc of 24 mm diameter and 7.8 mm in thickness. The upper ball was En 31 steel of 10 mm diameter. In present studies, discs were cut from En 31 steel rod and then heat treated to a hardness of 62 Rc. After heat treatment, grinding was done taking different depths of cut so that pieces of different roughness may be obtained. The disc specimen was mounted in such a way that sliding is perpendicular to the lay of roughness. After mounting the ball and disc specimens on SRV Optimol tester, a drop of commercial engine oil was applied at the contact zone for lubrication. The quantity applied was approximately 0.1 cm$^3$. The formulated oil contains zinc dithiophosphate besides other additives. The viscosity of the lubricant was 129.86 cSt at 40 °C and 13.29 cSt at 100 °C. The load was then applied gradually to the desired value. Frequency was kept constant at 50 Hz while temperature and timer are set to desired value. Drive switch is pressed to reciprocate the ball and the stroke length is increased slowly to the desired value of 1 mm. Total
duration was 8 h with 10 tests of 10, 10, 20, 20, 30, 30, 60, 60, 120, 120 min. At each stage the specimens were cleaned with benzene and acetone and the ball scar diameter was measured along and across the sliding direction. The geometric mean of these two values was taken for calculating the wear volume as per the following equation [9]:

where,

\[ V = \frac{\pi d_i^4}{64r} \left( \frac{d}{d_i} \right)^{-1} \]  

(12)

Find \( a, V_s \) from Eqn. (8) and \( R \) from Eqn. (10)

- \( b_2 = b_a \) and \( \frac{b_a}{b_a} = 2.0 \)

Yes

- \( b_1 = b_a \)

No

- \( b_1 = b_a \)

Find \( a, V_s \) from Eqn. (8) and \( R \) from Eqn. (10)

- \( b_1 = b_a \) and \( \frac{b_a}{b_a} = 2.0 \)

Yes

- \( b_1 = b_a \)

No

- \( b_1 = b_a \)

Calculate \( V_o \) from Eqn. (4)

Print \( V_o, V_s, a \) and \( b \)
The above experiments were performed by selecting one third fraction of $3^3$ factorial design [8]. The values of variables selected were:

- Load: 20, 40 and 60 N
- Roughness ($R_q$): 0.35, 0.55 and 0.75 µm
- Temperature: 50, 100 and 150 °C

One additional experiment was done in each case to calculate the sum square of error of experiments. The wear volume calculated for the ball at different time intervals was used as input for the computer program to find running-in wear rate, running-in period and steady-state wear rate. This is based on the theoretical model described earlier. One sample of input and output obtained from the computer program as well as a comparison between theoretical and experimental values is given in Fig. 5. The complete results have been tabulated in Table 1. Column 8 of Table 1 shows the F-ratio at each operating condition. F-ratio was calculated by dividing mean sum square of regression to mean sum square of residual for checking adequacy of the model. F-ratio varies from 294 to 3461 under different operating condition, while F-value at 99% confidence is 9.55 for the degree of freedom (2,7). This shows that the model represents wear data adequately. With regard to the disc only wear volume at the end of the experiment was determined for the selected cases and included under Section 4.

### Table 1

<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Root mean square value of roughness ($\mu$m)</th>
<th>Bulk temperature (°C)</th>
<th>Replication number</th>
<th>Running-in wear rate $(\times 10^{-4})$ (mm$^3$/h)</th>
<th>Steady-state wear rate $(\times 10^{-5})$ (mm$^3$/h)</th>
<th>Running-in period (h)</th>
<th>F-ratio</th>
<th>Error, $\varepsilon_2$ $(\times 10^{-7})$ (mm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.35</td>
<td>150</td>
<td>1</td>
<td>3.28</td>
<td>1.00</td>
<td>1.02</td>
<td>454</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>100</td>
<td>2</td>
<td>5.53</td>
<td>1.59</td>
<td>1.56</td>
<td>1415</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>50</td>
<td>1</td>
<td>5.10</td>
<td>4.00</td>
<td>2.45</td>
<td>1166</td>
<td>9.55</td>
</tr>
<tr>
<td></td>
<td>40.05</td>
<td>150</td>
<td>1</td>
<td>7.14</td>
<td>3.44</td>
<td>1.28</td>
<td>353</td>
<td>8.02</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>50</td>
<td>1</td>
<td>2.26</td>
<td>2.19</td>
<td>4.42</td>
<td>3461</td>
<td>6.62</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>50</td>
<td>2</td>
<td>3.89</td>
<td>2.60</td>
<td>3.88</td>
<td>1242</td>
<td>9.51</td>
</tr>
<tr>
<td>40</td>
<td>0.55</td>
<td>150</td>
<td>1</td>
<td>7.14</td>
<td>1.34</td>
<td>0.81</td>
<td>508</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>100</td>
<td>2</td>
<td>8.84</td>
<td>1.94</td>
<td>1.22</td>
<td>1843</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>100</td>
<td>2</td>
<td>4.58</td>
<td>3.40</td>
<td>1.62</td>
<td>294</td>
<td>5.30</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>75</td>
<td>1</td>
<td>6.95</td>
<td>1.38</td>
<td>1.73</td>
<td>2299</td>
<td>2.56</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>75</td>
<td>2</td>
<td>9.29</td>
<td>2.72</td>
<td>1.29</td>
<td>2710</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>75</td>
<td>1</td>
<td>17.26</td>
<td>3.99</td>
<td>0.71</td>
<td>1704</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>150</td>
<td>2</td>
<td>10.21</td>
<td>9.24</td>
<td>0.76</td>
<td>749</td>
<td>7.00</td>
</tr>
</tbody>
</table>

4. Results and discussion

Wear results given in Table 1 have been analysed on the basis of ANOVA (analysis of variance) and empirical relations. ANOVA Table quantifies the significance of variables on the running-in wear rate, running-in period and steady-state wear rate. Variance analysis is given in Table 2.

The running-in period was determined by selecting the value of $p$ as 95% in Eq. (11). The corresponding error, $\varepsilon_2$, in determining wear volume at this completion of the running-in was found to be in the order of $10^{-7}$ mm$^3$ as shown in the last column of Table 1. The error $\varepsilon_2$ in this table is obtained by finding the difference in wear volumes at $t_1$ by using Eqs. (6) and (7), respectively. The maximum error in calculating the wear volume of scars was estimated to be...
The value of $p$ (Eqn. (11)): 95

<table>
<thead>
<tr>
<th>Time, $t$ (hours)</th>
<th>Wear Volume ($\text{mm}^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17 8.46e-1</td>
<td>7.79e-5</td>
</tr>
<tr>
<td>0.33 7.17e-1</td>
<td>9.41e-5</td>
</tr>
<tr>
<td>0.67 5.13e-1</td>
<td>11.55e-5</td>
</tr>
<tr>
<td>1.0 6.84e-1</td>
<td>14.53e-5</td>
</tr>
<tr>
<td>1.5 2.32e-1</td>
<td>16.02e-5</td>
</tr>
<tr>
<td>2.0 1.35e-1</td>
<td>17.00e-5</td>
</tr>
<tr>
<td>3.0 4.99e-2</td>
<td>18.65e-5</td>
</tr>
<tr>
<td>4.0 8.32e-2</td>
<td>18.65e-5</td>
</tr>
<tr>
<td>6.0 2.48e-3</td>
<td>22.31e-5</td>
</tr>
<tr>
<td>8.0 3.56e-4</td>
<td>25.64e-5</td>
</tr>
</tbody>
</table>

$X$: Matrix $X_i$ to find Matrix $X$ for a particular value of $b$ (Eq.(9))
$Y$: Wear volume matrix at different time interval

(a) running-in wear rate=5.53e-04 steady state wear rate=1.59e-05
running-in period=1.56
$F$-ratio for checking adequacy of the model=1414.52
Error in wear volume determination at the completion of running-in=2.02e-07

(b) 10$^{-3}$ mm$^3$ based on the measurement precision of 0.01 mm in scar diameter. It is, hence, considered that selection of $p$ as 95% is justified.

To develop empirical relations, the assumed polynomial for the running-in wear rate, running-in period and steady-state wear rate is given below:

$$\log_e Y = a_0 + a_1 \log_e P + a_2 \log_e R_q + a_3 \log_e T_c$$ (17)

The coefficients of equations were found by Eq. (8), where $X$, $Y$ and $A$ matrices are

$$X = \begin{bmatrix} 1 & \log_e P_0 & \log_e R_{q0} & \log_e T_{c0} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \log_e P_n & \log_e R_{qn} & \log_e T_{cn} \end{bmatrix}$$

$$Y = \begin{bmatrix} \log_e w_{r1} \\ \vdots \\ \log_e w_{rn} \end{bmatrix}$$

$$A = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix}$$ and $n = 9$ (18)

Fig. 5. Sample of input (a); output (b) and comparison of experimental data and results obtained from the computer program (c) under operating conditions: 20N load, 0.35 [um] roughness, 150°C temperature and second replication.
where $T_c$ is the sum of bulk temperature $T^*$ and frictional temperature rise $A6_t$ at thejth set of operating condition. The value of $A6_t$ ranged from 4.5 to 18.5 °C. The temperature rise calculations were based on geometric contact area. Since progressive wear increases the geometric area of contact, the temperature rise at 10min, at the time of completion of running-in period was obtained from Eq. (6). In the development of empirical relation for the running-in wear rate rise was taken as zero at time $t = 0$. For developing empirical relations for running-in period average of $A6_t$ and $A6_t$ were taken as temperature rise which represents the running-in zone. For developing steady-state wear rate equation average of $A6_t$ and $A6_t$ were taken as temperature rise. The temperature rise $A0_t$ was estimated by the procedure adopted by Suh [10].

The empirical relations for the running-in wear rate, running-in period, and steady-state wear rate are given below:

$$\log w = -10.47 + 0.56 \log P + 0.99 \log R_c + 0.38 \log T_c, \quad (19)$$

$$\tau = \frac{2.85 \times 10^{-3} P^{0.96} R_c^{0.99} T_c^{2.24}}{R_s}, \quad (20)$$

$$\log w = -8.90 + 0.74 \log P + 0.95 \log R_c + 0.79 \log T_c, \quad (21)$$

Disc wear was estimated after the total test duration of 8 h. The disc was not removed during the experiments due to the problem of relocation. The schematic diagram of the disc scar is shown in Fig. 6. The profile of worn scar was traced at the middle portion along the sliding direction using Talystep instrument. A computer program was developed to find the wear volume. This program requires average length $l$, average width $w$, average extension of worn scar from rectangular portion $x$ and average depth of scar $δ$. The results of selected scars are given in Table 3. In this Table, the final wear volume of ball scar at different operating conditions are also given in column 2 in increasing order. Column 3 shows the corresponding wear volume of final disc scar. This column shows that disc wear is more than the ball wear. The linear relation between the two showed a correlation coefficient of 0.9935. Regression equation obtained is given below:

$$y_{disc} = 1.466 l + 1.52 \times 10^{-4} \quad (22)$$

From this information it is reasonable to assume that the influence of the various parameters on the ball wear rate will have similar trends for the disc wear also. The difference in absolute values may be related to the microstructure of the disc as compared to that of the ball.

Table 2: ANOVA tables for (a) running-in wear rate; (b) running-in period and (c) steady-state wear rate.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares (x10^{-4})</th>
<th>Degree of freedom (d.f.)</th>
<th>Mean sum of squares (x10^{-4})</th>
<th>F-ratio</th>
<th>F-tab at 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>7.32</td>
<td>2</td>
<td>3.66</td>
<td>10.57</td>
<td>4.26</td>
</tr>
<tr>
<td>Roughness</td>
<td>13.12</td>
<td>2</td>
<td>6.56</td>
<td>18.95</td>
<td>4.26</td>
</tr>
<tr>
<td>Temperature</td>
<td>5.59</td>
<td>2</td>
<td>2.79</td>
<td>8.07</td>
<td>4.26</td>
</tr>
<tr>
<td>Error</td>
<td>3.12</td>
<td>9</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>4.63</td>
<td>2</td>
<td>2.32</td>
<td>10.60</td>
<td>4.26</td>
</tr>
<tr>
<td>Roughness</td>
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<td>1.72</td>
<td>7.86</td>
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</tr>
<tr>
<td>Temperature</td>
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<td>3.05</td>
<td>13.97</td>
<td>4.26</td>
</tr>
<tr>
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<tr>
<td>(c)</td>
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<tr>
<td>Load</td>
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<td>0.83</td>
<td>33.34</td>
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<td>60.12</td>
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<td>Temperature</td>
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<td>1.39</td>
<td>55.42</td>
<td>4.26</td>
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<tr>
<td>Error</td>
<td>0.23</td>
<td>9</td>
<td>0.03</td>
<td></td>
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</tr>
</tbody>
</table>
4.1. Significance of variables

From ANOVA Table 2, it can be seen on the basis of tabulated errors that the initial running-in wear and running-in period have relatively poor repeatability. This is also shown in Table 1 where variations in repeat experiments are given. These variations are not unusual since the initial running-in part is strongly influenced by minor variations in the initial contact conditions. The steady-state wear showed good repeatability since the wear is estimated at \( t = \infty \) despite some variations in the running-in process.

The ANOVA table further shows that all parameters, load, temperature and initial roughness have significant influence on the wear rates and running-in period.

4.2. Empirical relations

The empirical relations given in Eqs. (19)—(21) show the importance of each parameter effectively. The Eq. (21) for steady-state wear shows that influence of initial roughness is a major factor since steady-state wear rate is related to \( R_0^{0.95} \). Thus the steady-state wear rate increased with roughness. The temperature influence \( T^{-0.095} \) shows that wear rate decreased with temperature. This is considered to be due to the quasi equilibrium film that forms after long duration due to the chemical additives in the lubricant as well as oxides. Within the temperature range studied wear resistant film formation may be better with increasing temperature. The final roughness reached by disc surface in all cases was \( R_q = 0.15 \) (im. Kragelsky [11] and Luenberger [12] also observed that surface roughness at steady-state conditions reached similar values despite the variations in initial roughness. However, the significant influence of initial roughness on steady-state wear is unexpected. The differences can not thus be explained on the basis of final roughness. The plausible reason is that the nature of films that evolve vary with initial roughness. Cavadar and Ludema [13] studied the growth of oxide films on steel

![Fig. 7. Auger spectrum from worn scar under operating conditions: 20N load, 0.75 \( \mu \text{m} \) roughness and 50°C temperature.](image-url)
discs of 45 Rc with mineral oil lubricant. They found that effective oxide film formation is time dependent. Similar effects may be occurring in the present case leading to low final steady-state wear. For initial lower roughness the films formed may have better mechanical adherence in comparison to the cases with higher roughness. Limited Auger spectroscopy was also conducted on worn scars of three surfaces. The film thickness ranged from 0.06 to 0.12 μm on the basis of variation in sulphur and oxygen with sputtering time. A typical example of Auger spectrum is given in Fig. 7. A correlation was not observed between film thickness and steady-state wear in these limited experiments. The reason for variations in steady-state wear may lie in the mechanical nature of films. At present, attempts are being made to evaluate this aspect by studying the response of worn films in reciprocating sliding with fresh steel balls.

Initial running-in wear rate as expressed by Eq. (19) shows that increased load, roughness and temperature increase the running-in rate. The positive exponent for temperature is because the reaction films are not formed and the wear may be governed mainly by physical adsorption.

The running-in time decreases with roughness unlike the steady-state wear. This is because steady-state is reached faster with rougher surfaces. The negative exponent for roughness in the steady-state equation. Running-in time also decrease with load as expected. The wear is not proportional to the load. For example in the case of steady-state wear rate the exponent is 0.74. This may be because of the changing contact area and film effects. This issue has to be further investigated.

5. Conclusions

1. A mathematical model has been developed to characterise the running-in wear rate at time zero, running-in period, and steady-state wear rate from the experimental wear data.

2. On the basis of designed experiments, the mathematical model has been used for developing empirical relations for running-in wear rate, running-in period and steady-state wear rate as a function of load, roughness and temperature.

3. Initial roughness was found to be the most significant parameter for steady-state wear rate. The wear rate increased with increasing roughness though final roughness of all specimens reached the same roughness of 0.15 μm.

4. Temperature was found to be the second most significant parameter for steady-state wear rate. The wear rate decreased with temperature. This is considered to be due to the reaction films formed.

5. The exponents in the equations for running-in wear rate and running-in time could be explained from the expected tribological behaviour.

References