Slurry Pump Gland Seal Three Body Wear

and the Influence of Particle Properties including

Hardness, Size, Fracture Toughness and Shape

by

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Doctor of Philosophy

in

Chemical Engineering

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DECLARATION

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Nigel Ian Ridgway ..........................
Date ..............................

NOMENCLATURE
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Cw</td>
<td>slurry percent solids by weight</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>crack flaw size</td>
<td>µm</td>
</tr>
<tr>
<td>an</td>
<td>regressor coefficient</td>
<td></td>
</tr>
<tr>
<td>ASPQ</td>
<td>adjusted spike parameter quadratic</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>constant</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>shaft sleeve diameter</td>
<td>m</td>
</tr>
<tr>
<td>d85</td>
<td>equivalent particle size 85% passing</td>
<td>µm</td>
</tr>
<tr>
<td>DH</td>
<td>hydraulic diameter</td>
<td>mm</td>
</tr>
<tr>
<td>ep</td>
<td>end point for boundary walk</td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td>form factor</td>
<td></td>
</tr>
<tr>
<td>GIC</td>
<td>critical crack energy release rate</td>
<td>J/m²</td>
</tr>
<tr>
<td>(GIC)Gb</td>
<td>GIC for grain boundary fracture</td>
<td>J/m²</td>
</tr>
<tr>
<td>(GIC)IF</td>
<td>GIC for interfacial fracture</td>
<td>J/m²</td>
</tr>
<tr>
<td>(GIC)IP</td>
<td>GIC for interphase fracture</td>
<td>J/m²</td>
</tr>
<tr>
<td>h</td>
<td>boundary layer thickness (also gap between packing and shaft sleeve)</td>
<td>µm</td>
</tr>
<tr>
<td>H</td>
<td>hardness</td>
<td>Mohs or Vickers scale, GPa</td>
</tr>
<tr>
<td>Ha/Hs</td>
<td>relative hardness of abrasive to surface</td>
<td></td>
</tr>
<tr>
<td>Hb</td>
<td>bulk hardness</td>
<td>Vickers</td>
</tr>
<tr>
<td>HPacking</td>
<td>theoretical macro hardness of packing</td>
<td>Vickers</td>
</tr>
<tr>
<td>Hshaft</td>
<td>hardness of shaft sleeve</td>
<td>Vickers</td>
</tr>
<tr>
<td>Hv</td>
<td>Vickers hardness</td>
<td>Vickers</td>
</tr>
<tr>
<td>K</td>
<td>packing lateral pressure ratio (also dimensionless wear coefficient)</td>
<td></td>
</tr>
<tr>
<td>KIC</td>
<td>fracture toughness stress intensity factor</td>
<td>MPa.m⁰.⁵</td>
</tr>
<tr>
<td>L</td>
<td>load (also effective packing contact length)</td>
<td>N (mm)</td>
</tr>
<tr>
<td>I</td>
<td>packing length/stuffing box depth</td>
<td>mm</td>
</tr>
<tr>
<td>L³/D⁴</td>
<td>shaft slenderness ratio</td>
<td></td>
</tr>
<tr>
<td>mp</td>
<td>mid point for boundary walk</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>pressure (gauge), (also contact load)</td>
<td>kPa, (N)</td>
</tr>
<tr>
<td>p(x), PR</td>
<td>radial packing pressure</td>
<td>kPa</td>
</tr>
<tr>
<td>PDN</td>
<td>particle dimensionless number</td>
<td></td>
</tr>
<tr>
<td>PMED</td>
<td>pump wet end fluid pressure</td>
<td>kPa</td>
</tr>
<tr>
<td>Q</td>
<td>flow rate</td>
<td>L/min</td>
</tr>
<tr>
<td>q(x)</td>
<td>packing radial pressure distribution</td>
<td>kPa</td>
</tr>
<tr>
<td>R</td>
<td>reaction force</td>
<td>N</td>
</tr>
</tbody>
</table>
\( r_{\text{apex}} \)  particle equivalent circle radius to vertex  \( \mu \text{m} \)

\( R_e \)  Reynolds Number

\( RF \)  roundness factor

\( r_{\text{mean}} \)  particle equivalent circle radius  \( \mu \text{m} \)

\( \text{rpm} \)  rotating speed  revolutions per minute

\( s \)  packing thickness, (also travel distance)  \( \text{mm} \)

\( \text{SD} \)  standard deviation

\( \text{SEM} \)  scanning electron microscopy

\( \text{sp} \)  starting point for boundary walk

\( \text{SPL} \)  spike parameter linear

\( \text{SPQ} \)  spike parameter quadratic

\( \text{SV} \)  spike value

\( \text{SWR} \)  specific wear rate  \( \text{mm}^3/\text{N.m} \)

\( t \)  time (also packing thickness)  hr, min, s (mm)

\( t_c \)  cutting chip thickness  \( \mu \text{m} \)

\( v \)  velocity  \( \text{m/s} \)

\( W \)  wear volume removed  \( \text{mm}^3 \)

\( \text{WDA} \)  weighed dihedral angle

\( x_n \)  regressor variable

\( Y \)  crack shape geometry factor

\( \alpha \)  cutting rake angle  \( \circ, \text{rad} \)

\( \delta \)  packing residual stress after adjustment  \( \text{kPa} \)

\( \Delta P \)  pressure differential  \( \text{kPa} \)

\( \varepsilon \)  packing deformation

\( \theta \)  cutting attack angle  \( \circ, \text{rad} \)

\( \mu \)  fluid viscosity  \( \text{Pa.s} \)

\( \mu_1 \)  packing friction

\( \rho_{\text{shaft}} \)  density of shaft material  \( \text{kg/m}^3 \)

\( \sigma(x) \)  axial packing stress distribution  \( \text{kPa} \)

\( \sigma_c \)  critical crack tensile stress  \( \text{Pa} \)

\( \sigma_D \)  gland follower applied stress  \( \text{kPa} \)

\( \sigma_k \)  packing stress at stuffing box bottom  \( \text{kPa} \)

\( \Phi \)  cutting shear angle  \( \circ, \text{rad} \)

\( \Psi \)  particle vertex dihedral angle*  \( \circ, \text{rad} \)

*Note that the dihedral angle of a particle (which is the angle between two surfaces of a vertex) is described in the literature with a range of symbols including \( 2\Psi \), \( 2\alpha \), and \( \Psi \). \( \Psi \) is also used by some authors to represent the attack angle, \( \theta \).
**Regression**

- $C_{ij}$: covariance matrix of regression
- $df/da_n$: partial derivative for non-linear regression model
- $F$: test statistic
- $F_{ij}$: matrix of observation data
- $k$: number of regressor variables
- $MSE$: mean square residual error of regression
- $MSR$: mean square of regression
- $n$: number of observations
- $p$: test of significance for regression
- $R^2$: coefficient of multiple determination
- $S^2$: approximate $MSE$, estimated error variance
- $SA$: square of averages
- $SSE$: sum square of errors
- $SSR$: sum square of regression
- $SSR_T$: sum square of total errors
- $t$: test of confidence

**Reliability**

- $F(t)$: unreliability function
- $MTBF$: mean time between failures $\text{hr}$
- $MTTR$: mean time to repair $\text{hr}$
- $P(t)$: probability of failure at time $t$
- $\beta$: shape parameter
- $\gamma$: location parameter
- $\varepsilon$: Weibull analysis goodness of fit
- $\eta$: characteristic life parameter
- $\lambda$: failure rate
- $\mu$: mean time to repair (MTTR) $\text{hr}$
- $\sigma$: standard deviation of time to repair
SUMMARY

Gland sealing has been researched since the 1950’s by the British Hydraulic Research Association and others to improve seal performance. The literature review showed the focus had been on uniform packing compression to more closely match the packing pressure distribution to the fluid pressure with the objective of reducing leakage over time. There was limited work on the tribology of gland sealing and the patents were dominated by seal designs in a liquor environment. The review identified the particle properties of hardness, shape, fracture toughness and size as relevant to the wear and useful life of a gland seal in a slurry environment. This research presents the design, development and testing of a novel laboratory test rig which deliberately injects slurry particles into a typical standard slurry pump gland seal to cause wear of the sacrificial shaft sleeve. Mineral processing relies on slurry pumping to transfer slurry between plant operations and to improve life cycle costs and reliability in the long term a tribology approach was employed for the research.

A range of mineral and synthetic particles were selected over the widest possible hardness range, tested and correlated with the output variable (specific wear rate) of the shaft sleeve. The wear of the shaft sleeve was normalised by travel distance and gland follower load. The data was combined by a novel empirical regression wear model which unified the controlling variables of load, travel distance, particle size, hardness, fracture toughness and size. Recent published values of hardness and fracture toughness were included in the analysis. A linear regression model with interactive terms between the fracture toughness, particle size and hardness, including a log term for the size, provided a good fit with statistical significance to the experimental data. Some dependency was demonstrated between the controlling variables of fracture toughness and particle size.

Particle shape was found not to be relevant to the model for particle sizes less than 500 microns. A novel particle shape descriptor weighted dihedral angle which described the average dihedral angle of
particle vertices, was proposed and this did not provide any more accuracy than existing descriptors such as SPQ.

It was discovered during the experiments that slurry particles may form quasi particles in the seal gap depending on the geometric parameters, gap dimension and material parameters of the opposing (packing) surface, in a semi continuous process. A new tribology qualitative model for the wear of the shaft sleeve and motion of the particles in the gap is described.

The relevant particle properties have also been combined into a novel dimensionless number \( (P_{DN}) \) which was found to provide a significant correlation with the shaft sleeve SWR, and therefore has the potential to serve as the basis for future research investigation in three body wear.
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