FE macro/micro models for contact temperature analysis of a steel asperity sliding over a normally oriented CF/PEEK composite surface

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Abstract

FE contact and thermal macro/micro models have been developed to study the real thermal behaviour of a fibre/matrix micro-structure under sliding motion of a steel asperity. At first the contact parameters were evaluated using an approximate contact technique, followed by a transient thermal FE evaluation. The latter considers the heat partition between the steel asperity and the real fibre/matrix micro-environment of a normally oriented CF/PEEK composite.

1 Introduction

The friction and wear behaviour of fibre reinforced composites has been intensively studied in the last couple of years in order to improve the tribological performance of these materials. In particular, different efforts were undertaken to better understand both the wear rates of composites against steel counterparts and the corresponding wear mechanisms.

Between sliding bodies frictional heat is generated, increasing the temperature of the elements, until a thermal steady state condition has been reached. The temperature in the vicinity of the contact area affects the mechanical properties and the wear resistance of the components, especially in
the case of polymers where a temperature difference of 100 °C can already cause drastic changes. Due to this fact, wear mechanisms cannot be explained without knowing the thermal conditions.

The heat generation arises at the spots of real contact between the two bodies, thus producing local temperature rise, which in time, heats up the whole bodies; the latter effect is called nominal temperature rise. Tian and Kennedy [1] studied this problem in great detail, and they were able to evaluate the total contact temperature at the interface from the asperity scale and the nominal contact temperature rise values. In this material the contact temperature means the asperity scale contact temperature rise.

To evaluate the contact parameters of rough surfaces different models were developed in the last two decades [2]. In the earlier analytical and numerical solutions, elastic models were applied, later elastic-plastic or plastic models with different plastic limit pressure ($p^*$) conditions [2] were introduced.

Anisotropic contact problems were studied in [3]. In these works the plane of isotropy was oriented normal to the plane of contact. Váradi et al. extended their isotropic contact algorithm to solve anisotropic contact problems [4] by using the influence matrix approach; the elements of the anisotropic influence matrix were obtained by coupled FE models.

The contact temperature development was studied by analytical and numerical models. Archard [5] studied moving heat sources and calculated the mean and maximum contact temperatures considering the heat partitions, too.

To evaluate the contact temperature distribution, in the case of anisotropic materials, Ovaert and Talmage [6] introduced band and rectangular patch heat source models. For the same problem Váradi et al. [7] developed a numerical thermal algorithm for the stationary problems. They also used FE transient thermal analysis in case of "intermediate and fast sliding" problems and introduced a definition for composite Peclet numbers.

The present examination focuses on the contact and thermal analysis of composite-steel surfaces using micro-models, "built into" a larger (homogeneous and anisotropic) macro-model, in order to consider the real behaviour of the fibre/matrix micro-structure. (The FE micro-model is always very small (example 0.1 mm x 0.1 mm), while the of degrees of freedom (DOF) is in the range of 100,000.)

The aim of the present investigation is to evaluate the contact temperature rise in the case of macro/micro-models, and to compare the results with those obtained by macroscopic models. In order to compare these results, data, similar to [7], were taken considering the size and loading of the modelled steel asperity, furthermore the material properties of the composite structure.

The problem specified was solved by contact and transient thermal FE techniques. At first, the actual contact area and contact pressure distribution were evaluated for the case of an asperity in sliding motion over a fibre/matrix micro-structure, followed by the contact temperature analysis, using a moving heat source model associated with the actual contact results.
2 The contact temperature evaluation

2.1 Peclet-number and heat partition evaluation

The Peclet number for isotropic bodies in sliding contact [1] is defined as

\[ Pe = \max \left\{ \frac{va}{2k^{(1)}}, \frac{va}{2k^{(2)}} \right\}, \tag{1} \]

where \( v \) is the sliding speed, 
\( a \) is the radius of the contact area, 
\( k^{(1)}, k^{(2)} \) are the thermal diffusivities of body (1) and (2).

In the present case, body (1) represents the steel asperity, and body (2) represents the CF/PEEK composite material. A steady state heat conduction solution can be used, i.e. the “slow sliding” condition is valid, if the Peclet number \( Pe \leq 0.5 \). The “fast sliding” assumption is valid for \( Pe > 5 \) [1].

For anisotropic bodies, following the macroscopic approach, heat conductivity is different in the principle material directions. In [7] composite Peclet-numbers were defined for normal (N), parallel (P) and antiparallel (AP) fibre orientations. In each case Peclet numbers in \( x, y \) and \( z \) directions are different. In the present case, i.e for N-fibre orientation, the composite Peclet-numbers are defined as follows:

\[ (Pe)_{N_x} = \frac{va}{2k^{(2)}_{22}}, \quad (Pe)_{N_y} = \frac{va}{2k^{(2)}_{33}} \quad \text{and} \quad (Pe)_{N_z} = \frac{va}{2k^{(2)}_{11}}, \tag{2} \]

The thermal diffusivities are:

\[ k_{11} = \frac{K_{11}}{\rho_c c_c}, \quad k_{22} = \frac{K_{22}}{\rho_c c_c} \quad \text{and} \quad k_{33} = \frac{K_{33}}{\rho_c c_c}, \tag{3} \]

where \( K_{11}, K_{22} \) and \( K_{33} \) are the anisotropic thermal conductivities of the composite material, furthermore \( \rho_c \) and \( c_c \) are the composite density and the composite specific heat respectively, obtained by rule of mixture approaches.

The total generated heat \( Q \) can be calculated if the total friction energy is assumed to be converted into heat:

\[ Q = \mu v F, \tag{4} \]

where \( \mu \) is the coefficient of friction, and
\( F \) is the applied normal load.

The heat generated is partitioned between body (1) and (2) according to the condition, that the contact temperature should be the same inside the real contact area at every point pair belonging to body (1) and (2). The heat partition \( \alpha \)
represents the proportions of heat $Q^{(1)}$ and $Q^{(2)}$ supplied to body (1) and (2) in the following way:

$$Q^{(1)} = (1 - \alpha)Q \quad \text{and} \quad Q^{(2)} = \alpha Q.$$  \hspace{1cm} (5)

According to Tian and Kennedy's [1] suggestion, the maximum contact temperature is

$$T_{\text{max}} = \alpha \overline{T}_{\text{max}}^{(2)} = (1 - \alpha)\overline{T}_{\text{max}}^{(1)},$$ \hspace{1cm} (6)

where $\overline{T}_{\text{max}}^{(1)}$ and $\overline{T}_{\text{max}}^{(2)}$ represent the relative maximum temperatures if all the heat generated is assumed to be transmitted to either body (1) or body (2). Expressing the heat partition from eqn 6 leads to

$$\alpha = \frac{\overline{T}_{\text{max}}^{(1)}}{\overline{T}_{\text{max}}^{(1)} + \overline{T}_{\text{max}}^{(2)}}.$$ \hspace{1cm} (7)

For anisotropic bodies, these equations (5-7) will produce approximate results due to their isotropic validity.

### 2.2 FE macro/micro contact models

The contact temperature development can only be studied if the contact problem is solved, at first, at the representing positions of the sliding motion.

If a modelled, spherical steel asperity is sliding over a composite micro-structure, different shape of contact area and contact pressure distributions will represent the sliding motion. Figure 1 shows the sliding asperity along two lines. One is located between the fibers; the other is along the centerline of the fibers.

![Figure 1: The "sliding path" between the fibers (a) along centerline of the fibers (b)](image)

The contact problem is solved in an approximate way, furthermore a linear elastic material law for both the fibers and matrix is considered. The FE technique would allow a more accurate analysis (using non-linear material law), but in the present case where the degrees of freedom is already 59410 and
contact solutions are needed for many consecutive steps, this would require much more CPU time.

The FE mesh for the contact analysis is shown in Figure 2. The size of the micro-segment is 0.0288 mm x 0.0096 mm x 0.054 mm. To consider a larger portion of this environment, a macro-model is used around the micro-one. The micro-model part contains 17493 nodes and 15360 elements; furthermore the connecting macro-model contains 21630 nodes and 20000 elements. The material properties are listed in Table 1 for the fibers, the matrix, and the composite macro-model.

![Figure 2: FE mesh of the macro/micro model and the detailed view of the micro-segments for cases shown in Figure 1](image)

### 2.3 FE transient thermal macro/micro models

The aim of this section is to solve the moving heat source problem for the composite body, and to evaluate the steady state thermal problem for the asperity, while the heat partition is also considered. In the transient FE model, different heat source values are assigned to the elements, at every time step, representing the moving contact areas.

Considering the FE mesh the FE thermal model is the same as the FE model for contact calculation. The heat source moves to the next location as the contact pressure distribution does. The transient heat conduction problem is repeatedly solved using a smaller time increment than the mentioned time step. The time step, within which a set of heat sources is staying at a certain location, depends on the size of the elements and the sliding speed. The boundary conditions are a
prescribed temperature of zero degrees along the three side surfaces and the bottom surface, furthermore the plane of the symmetry is isolated (Figure 2).

3 Results and discussion

3.1 The problem studied

The material properties are collected in Table 1. The mechanical and thermal properties of the composite material were calculated by "rule of mixture" type equations.

Table 1. Mechanical and thermal properties of the materials in sliding contact

<table>
<thead>
<tr>
<th></th>
<th>Steel</th>
<th>CF</th>
<th>PEEK</th>
<th>CF/PEEK (calculated)</th>
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<tbody>
<tr>
<td>$V_f$=0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{11}$ [MPa]</td>
<td>235000</td>
<td></td>
<td></td>
<td>142440</td>
</tr>
<tr>
<td>$E_{22}$ [MPa]</td>
<td>210000</td>
<td>15000</td>
<td>3600</td>
<td>6618</td>
</tr>
<tr>
<td>$E_{33}$ [MPa]</td>
<td>15000</td>
<td></td>
<td></td>
<td>6618</td>
</tr>
<tr>
<td>$G_{12}$ [MPa]</td>
<td>6432</td>
<td></td>
<td></td>
<td>2932</td>
</tr>
<tr>
<td>$G_{13}$ [MPa]</td>
<td>80769</td>
<td>6432</td>
<td>1286</td>
<td>2932</td>
</tr>
<tr>
<td>$G_{23}$ [MPa]</td>
<td>5357</td>
<td></td>
<td></td>
<td>2196</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.166</td>
<td></td>
<td></td>
<td>0.26</td>
</tr>
<tr>
<td>$\nu_{13}$</td>
<td>0.3</td>
<td>0.166</td>
<td>0.4</td>
<td>0.26</td>
</tr>
<tr>
<td>$\nu_{23}$</td>
<td>0.4</td>
<td></td>
<td></td>
<td>0.507</td>
</tr>
<tr>
<td>$K_{11}$ [W/mK]</td>
<td>16</td>
<td></td>
<td></td>
<td>10.6</td>
</tr>
<tr>
<td>$K_{22}$ [W/mK]</td>
<td>50</td>
<td>3</td>
<td>0.25</td>
<td>0.555</td>
</tr>
<tr>
<td>$K_{33}$ [W/mK]</td>
<td>3</td>
<td></td>
<td></td>
<td>0.555</td>
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<tr>
<td>$\rho$ [kg/m$^3$]</td>
<td>7850</td>
<td>1780</td>
<td>1320</td>
<td>1596</td>
</tr>
<tr>
<td>$c$ [J/kgK]</td>
<td>460</td>
<td>750</td>
<td>1300</td>
<td>932</td>
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<tr>
<td>$k_{11}$ [m$^2$/s]</td>
<td>$12\times10^{-6}$</td>
<td></td>
<td></td>
<td>$7.13\times10^{-6}$</td>
</tr>
<tr>
<td>$k_{22}$ [m$^2$/s]</td>
<td>$13.8\times10^{-6}$</td>
<td>$2.24\times10^{-6}$</td>
<td>$0.146\times10^{-6}$</td>
<td>$0.373\times10^{-6}$</td>
</tr>
<tr>
<td>$k_{33}$ [m$^2$/s]</td>
<td>$2.24\times10^{-6}$</td>
<td></td>
<td></td>
<td>$0.373\times10^{-6}$</td>
</tr>
</tbody>
</table>

The size and the load of the asperity, furthermore the material properties are the same as they were in [7] for further comparison. The input data used are as follows:

- asperity radius: $R=10\ \mu$m,
- normal load: $F=0.01\ \text{N},$
- sliding speed: $v=1\ \text{m/s},$
- coefficient of friction: $\mu=0.45.$
3.2 Contact results

The contact pressure results are presented in Figures 3 and 4 for the two different cases (see Figure 1) together with the contact temperature results. Figure 3 shows the results at locations a to e (between the fibers), representing half of a symmetrical segment of the sliding path. At first, the contact area is smaller due to the nearer fibers, but finally the asperity is located at a region where more matrix yielding could occur in a larger contact area, resulting in a smaller contact pressure maximum. After position e, in the next unit, the same results in an opposite order will represent the contact conditions.

Figure 4 reflects the contact results along the centerline of the fibers. At position a, a small contact area and a high contact pressure maximum characterize the case. Moving nearer to the edge of the fibre, a wider contact area and a reduced contact pressure maximum appear. Location e finally represents the case, where the matrix and the nearest two fibers are positioned symmetrically.

3.3 Contact temperature results

Reviewing the Peclet numbers first, two special cases are of interest. In Table 2 “between fibers” represents the location e of the case shown in Figure 1a, where mostly matrix carries the load. At this position, therefore, only matrix thermal properties were considered in eqn 3. In Table 2 “fibers centerline” represents the location a of the case shown in Figure 1b; here mainly the fibers are loaded, so that only the fibre properties were taken. Results, assigned as “macro” in Table 2, were obtained by using composite properties calculated by a “rule of mixture” approach.

<table>
<thead>
<tr>
<th></th>
<th>2a_{av} [μm]</th>
<th>(Pe)_x^{(2)}</th>
<th>(Pe)_y^{(2)}</th>
<th>(Pe)_z^{(2)}</th>
<th>α</th>
<th>T_{av} °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>between fibers</td>
<td>5.4</td>
<td>9.25</td>
<td>9.25</td>
<td>9.25</td>
<td>0.023</td>
<td>10.25</td>
</tr>
<tr>
<td>fibers centerline</td>
<td>3.0</td>
<td>0.33</td>
<td>0.33</td>
<td>0.06</td>
<td>0.086</td>
<td>16.43</td>
</tr>
<tr>
<td>macro</td>
<td>3.0</td>
<td>2.01</td>
<td>2.01</td>
<td>0.11</td>
<td>0.045</td>
<td>15.3</td>
</tr>
</tbody>
</table>

It can be concluded, that in the case of “between fibers” the matrix properties produce high Peclet numbers and “fast sliding” conditions, whereas in the case of “fibers centerline” “slow sliding” conditions are valid. In case of the “macro” model, in transversal direction, an intermediate state between “fast” and “slow sliding” conditions characterizes the behaviour.
In order to find the heat partition between the asperity and the composite components, the relative average contact temperatures \( T_{av}^{(1)} \) and \( T_{av}^{(2)} \) should be evaluated first; they are the result of the stationary (asperity side) and the moving heat source (composite side) solutions.

The contact temperature distributions at five representing steps are illustrated in Figures 3 and 4 on the surface of the composite micro-models.

Figure 3: Contact pressure and contact temperature distributions for the case that the "sliding path" is located between the fibers at locations \( a \) to \( e \) (see Figure 1a)
Figure 4: Contact pressure and contact temperature distributions for the case that the “sliding path” is located along the centerline of the fibers at locations a to e (see Figure 1a)

Conclusions

(a) The FE contact and thermal macro/micro models developed can represent the behavior of the fiber/matrix micro-environment. The contact parameters are different from location to location in sliding movement. According to the thermal results, the heat conduction is different if matrix or fibre is subjected to the heat source, so the heat partition is the lowest one if a matrix-reach environment is considered and the possible highest one if fibre is loaded by the asperity. In the latter case the contact area is smaller and pressure maximum is higher,
producing higher contact temperature than in the case if matrix-environment is loaded, where the contact area is larger and the contact pressure maximum is lower.

(b) In the heat condition problem the steel asperity dominates. The heat partition supplied into the asperity varies between 91.4-97.7%, in the cases studied. As a rough approximation, contact temperature can be calculated by assuming 100% heat transferred into the steel asperity and applying a steady state analytical solution, if the size of the contact area is known.

(c) In the present study the effect of a single sliding asperity was considered. In the real cases while a lot of asperities "are working", their combined effect will produce a higher contact temperature.

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References