Frictional Heat Generation in Selective Ceramic Reinforced Polymer Composites - Effect of Particle Size

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Abstract

Machine elements such as bushes, gear, and rollers made of polymer composites often fail by wear and/or contact fatigue. During service, the temperature of contacting machine elements increases because of heat generation due to friction and hysteresis and their properties degrade. The deterioration in the mechanical properties of polymer due to the accumulation of heat near the contact region causes accelerated wear and influence the performance of the parts. This research work focuses on reducing the surface temperature and increasing the wear resistance using selective ceramic reinforcement at the contact regions. This paper describes a method to predict the temperature rise due to friction under sliding condition using simplified numerical technique that will help in designing the surface reinforcement. The effect of particle size on the surface temperature distribution in the selective ceramic reinforced polyamide 6 composites is reported. The results reveal that the presence of ceramic particles at the contact region decreases the surface temperature considerably. The reduction in surface temperature increases with the increase in percentage area coverage by the particles. Presence of particles at the subsurface region enhances the heat transfer and effectively reduces the surface temperature. For a given volume fraction of particle in matrix, significant reduction in surface temperature can be achieved by placing large number of small size particles close to each other at the contact surface and subsurface regions.

Keywords: Polymer composites, Surface reinforcement, Frictional heating, Surface temperature prediction.

1 Introduction

In recent years, polymeric material gained significant importance in engineering field due to its beneficial characteristics. However, the low strength and stiffness limit the load carrying capacity of polymeric materials. Many researchers have attempted and succeeded in improving the physical properties of polymeric material through macro-, micro- and nano-size particles/ reinforcements and are described in detail by Friedrich (2005). The prime function of reinforcements in polymer matrix composites is to carry the load and the effectiveness depends on its orientation. Controlling the orientation of reinforcements during manufacturing process is difficult and hence in conventional composite machine components only a tiny fraction of reinforcement is utilized effectively to carry the load. This ineffective and uneconomical use of reinforcements can be overcome by selective reinforcement method. Several researchers were studied the performance of machine components made out of polymeric and polymer matrix composite and reported that wear is the major mode of failure, Kurokawa (2003); Senthilvelan (2004). Wear results in dimensional change and surface/sub-surface damage, which affect the performance and reduce the service life of the machine elements. The wear rate is inversely proportional to the surface hardness and, hence, the soft material like polymer undergoes significant wear, Yamaguchi (1990). Most of the polymer machine components are made from thermoplastics and at high temperatures materials soften resulting in substantial loss of strength. The further softening of polymer surface due to the heat accumulation accelerates the wear and results in excessive wear rate. Thus, the interface temperature also plays a major role in wear of polymeric materials. A design approach which can decrease surface heat accumulation in combination with increased surface hardness can enhance the tribological performance and service life of polymeric machine components. In this present work, an attempt is made to reduce the surface temperature and increase the wear resistance of polyamide 6 by selective reinforcement of...
ceramic particles at the contact regions. The effect of ceramic particle size on the surface temperature and its distribution near the contact region were studied using numerical methods and are reported here.

2 FE Modelling and Analysis

A 3D cubic representative volume element called unit cell containing the particles throughout the cube was used by many researchers to study the effective properties of conventional particulate composites, Rajlakshmi (2010); Bode (2014). The unit cell approach reduces the computational time significantly. To study the effectiveness of selective reinforcement method, a 3D cubic unit cell was constructed near the contact region with the particles only at one of the surface. The size of the unit cell and sliding time (analysis duration) were selected carefully to eliminate the effects of boundary condition. The ceramic particles were modelled with regular shape Johnson square pyramid. Fig. 1(a) to (d) shows the schematic diagram of selective reinforced object and unit cell (computational domain), 3D model of a single ceramic particle, neat polymeric cell and particle embedded polymeric cell respectively. The volume fraction of particle significantly affects the properties of composite materials. To study the effect of particle size alone, several unit cells were developed with constant volume fraction and with different particle size. The area coverage by the particles in the unit cell is increased without affecting the volume fraction by carefully selecting the particle size and the number of particles. In this study, unit cells with different particle size (635, 485, 400 and 345 µm) with different percentage area coverage (40.3, 52.8, 64.0 and 74.3) were developed and used. Particles at the subsurface region also affect the surface temperature distribution and hence separate models with particles at the subsurface were developed with afore mentioned particle size and area coverage. In all the unit cells the volume fraction of particle is maintained to a constant value (3.02% for one layer of particles; 6.04% for two layers of particles). In this study, polyamide 6 (PA6) and alumina (Al2O3) were considered as matrix and particle materials respectively and the material properties are shown in Table 1. The 3D models were developed in commercial modelling software and imported into finite element analysis software for subsequent analysis. The Al2O3 particles and PA6 matrix were meshed with 20-node thermal solid element. The 10-node tetrahedral thermal solid element without much distortion in the shape was used at the geometry transition regions. The thermal surface element was used at the contact regions to facilitate the application of heat flux boundary condition. The unit cell was assumed to have an initial temperature of 303 K (room temperature) and was assumed to slide with a velocity of 0.4 m/s under the contact pressure of 0.5 MPa with 0.3 coefficient of friction and equal heat partition between the two contacting objects.

Figure 1 (a) schematic diagram of selective reinforced object and unit cell, (b) model of single ceramic particle, (c) model of neat PA6 unit cell, and (d) model of PA6 unit cell with 400 µm particles at the surface with 64% area coverage.
Table 1. Properties of materials used

<table>
<thead>
<tr>
<th>Properties</th>
<th>PA6</th>
<th>Al2O3</th>
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<tbody>
<tr>
<td>Density (kg/m^3)</td>
<td>1140</td>
<td>3960</td>
</tr>
<tr>
<td>Thermal conductivity (W/m K)</td>
<td>0.29</td>
<td>30</td>
</tr>
<tr>
<td>Specific heat (J/kg K)</td>
<td>1700</td>
<td>880</td>
</tr>
<tr>
<td>Heat capacity (10^6 J/ m^3 K)</td>
<td>1.94</td>
<td>3.49</td>
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</tbody>
</table>

For the stated operating condition, the heat flux was calculated and applied at the contact surface of unit cell. All other surfaces were given insulated boundary condition to represent the periodic boundary condition. Rajlakshmi (2010); Bode (2014). The transient thermal finite element analysis was performed for 1 s with above mentioned initial temperature and boundary conditions. The FE models were first validated by comparing the analysis results with the analytical solution of the heat diffusion equation with constant heat flux boundary condition (Neumann condition) and then the effects of particle size and area coverage were studied. The analytical equation to find the temperature at any time, t and at any depth, z is given by Rohsenow (1998),

\[ T(z,t) = T_i + \frac{2q''}{\pi k} \exp\left(-\frac{z^2}{4\alpha t}\right) \frac{q''}{k} \text{erfc}\left(\frac{z}{2\sqrt{\alpha t}}\right) \]

where, \( \text{erfc} \) is the complementary error function, \( k \) is the thermal conductivity, \( q'' \) is the heat flux at the contact surface, \( T_i \) is the initial temperature of the unit cell, \( z \) is the distance from the contact surface, \( \alpha \) is the thermal diffusivity. The deviations in the results are within ±0.1%. The moulding and validation procedure are described in detail elsewhere, Gurunathan (2014).

3 Results and Discussion

The surface temperature raise during sliding and associated material property degradation influence the tribological characteristics and performance of polymeric machine components. The movement of free electrons and vibration of lattice cause the heat transfer within the materials. The free electrons dominate the phenomena in crystalline materials and lattice vibration dominates in amorphous materials. In general, materials with crystalline or ordered structure have high thermal conductivity compared to amorphous materials. In polymers, the heat transfer occurs mainly due to the vibration and rotation of chain molecules which is an ineffective mode of heat transfer and it is further affected by the amorphous phase. The amorphous phase in polymer restricts the movement and rotation of chains. As a result, the thermal conductivity of polymer tends to be very low and it depends on the degree of crystallinity or orderly arrangement of molecular chains. In this study the thermal properties of polymer surface are enhanced by embedding the ceramic particles.

The nodal temperature distribution at the contact surface (plane XY in Fig. 1) of unit cells is shown in Fig. 2(a) to (e). The heterogeneous nature of particle embedded PA6 cell results in non-uniform temperature distribution. The nodal temperature distribution plots show that embedding the ceramic particles at the contact surface reduces the surface temperature and the maximum temperature at the contact surface decreases with the decrease in particle size and increase in area coverage. Area weighted average temperature was used for the accurate representation of temperature over the surface area with non-uniform temperature profiles. The nodal temperatures obtained from the analysis were weighted by the amount of element face area associated with each node to compute the area weighted average temperature. A subroutine was developed and used in this study to compute the area weighted average temperature. Figure 3 (a) and (b) shows the area weighted average temperature within the unit cells with different particle size and constant particle volume fraction. Figure 4 shows the temperature reduction at the contact surface of Al2O3 particle embedded PA6 cells in comparison with the neat PA6 cell. These two figures reveal that the decrease in particle size decreases the surface temperature in the unit cells with constant volume fraction. The reduction in surface temperature increases with the increase in percentage area coverage and the presence of particles at the subsurface regions (increase in volume fraction). Better thermal properties of ceramic particle provides less resistant for heat transfer and creates an effective thermal conductive path. Increasing the number of particles and thus increasing the area coverage increase the number of effective conductive paths available at the surface and, hence, enhance the surface temperature reduction. The length of effective conductive path is also an important factor in enhancing the heat transfer from the contact region and it directly depends on the particle size. Increasing the particle size, increases the length and vice versa. There is a small difference in surface temperature between the unit cells with 400 µm and 345 µm Al2O3 particles due to small difference in particle size. However, the presence of particles at the subsurface forms a network of conductive path with adjacent particles. Providing more particles in depth direction increases the length and network of effective conductive path and hence the heat transfer from the contact surface is enhanced and reduces the surface temperature. Thus, to achieve significant reduction in
surface temperature using the selective reinforcement method, it is advisable to use large number of high thermal conductive particles close to each other for a relatively larger depth from the contact region. This will provide more number of effective conductive paths with small polymeric region in between the particles. The reduction in surface temperature and enhancement in surface hardness by the ceramic particles can reduce the wear in polymeric machine components.

Figure 2 Nodal temperature distribution in unit cells at the contact surface (XY plane) after sliding for 1 s.

Figure 3 Area weighted average temperature at different sections within the unit cells after sliding for 1 s.

Figure 4 Temperature reduction at the surface of Al2O3 embedded PA6 cells with constant volume fraction after sliding for 1 s with reference to neat PA6 cell.
4 Conclusions

The effect of embedding ceramic particles at the contact region in temperature distribution within polyamide 6 matrix was studied using transient thermal analysis. The analysis results reveal that embedding ceramic particles alters the temperature distribution near the contact region and reduce the surface temperature significantly. Presence of high thermal conductive ceramic particle reduces the thermal resistance, enhance the heat transfer, reduce heat accumulation and result in reduction in surface temperature. The reduction in surface temperature increases with decreasing the particle size and increasing the number of particles at the surface and the subsurface regions.

References